UNIVERSITY OF ÇUKUROVA
INSTITUTE OF NATURAL AND
APPLIED SCIENCES

MSc. THESIS

Ali Neşet KÜÇÜKALTUN

X-BAND MICROWAVE TRANSMISSION THROUGH WAVEGUIDE WITH VARIABLE LATERAL PERIODIC PROFILE

**DEPARTMENT OF ELECTRICAL AND
ELECTRONICS ENGINEERING**

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FEN BİLİMLERİ ENSTİTÜSÜ

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YÜKSEK LİSANS TEZİ

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ABSTRACT

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
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Analysis of electromagnetic wave propagation in periodic structures is of considerable interest due to their extensive use in many fields of electrical and optical engineering such as microwaves, antennas and radars, communications, optoelectronics, photonic crystals, fiber grating sensors.

The propagation of microwaves through different types of hollow metallic waveguides has been investigated. The aim of the thesis is to find a shape of walls that can stop transmission of electromagnetic radiation through the hollow metallic waveguide without closing its cross-section. For this purpose planar and rectangular waveguides with variable lateral periodic profile manufactured and setup for transmission measurements had assembled.

It was shown that microwave transmission depends on the relative position of two periodically corrugated plates. The transmission varies from zero to a maximum value upon shifting one periodic plate with respect to another on the half period of the corrugation. The results confirm the theoretical prediction of the geometry-driven spectrum transformation from the band structure spectrum to a gapless one upon such a shift of one of the plates.

Keywords: Planar waveguide, electromagnetic wave, periodicity, Bragg reflection.

ÖZ

YÜKSEK LİSANS TEZİ

DEĞİŞKEN YANAL PERİYODİK PROFİLE SAHİP DALGA KILAVUZU İÇİNDEN X-BAND MİKRODALGA İLETİMİ

Ali Neşet KÜÇÜKALTUN

ELEKTRİK-ELEKTRONİK MÜHENDİSLİĞİ BÖLÜMÜ
FEN BİLİMLERİ ENSTİTÜSÜ
ÇUKUROVA ÜNİVERSİTESİ

Danışman: Prof. Dr. Victor POGREBNYAK
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Prof. Dr. Hamide KAVAK
Yrd. Doç. Dr. Sami ARICA

Periyodik yapılarda elektromanyetik dalga yayılımının analizi, mikrodalgalar, antenler ve radarlar, haberleşme, optoelektronik, fotonik kristaller fiber grating sensörler gibi elektrik ve optik mühendisliğinin birçok alanında yaygın kullanım alanlarına sahip olduğu için hatırı sayılır ilgiye sahiptir.

Bu araştırmada farklı yapılarda olan içi boş metalik dalga kılavuzlarındaki mikrodalga yayılımı incelenmiştir. Bu araştırmanın amacı içi boş metalik dalga kılavuzundaki dalga yayılımını, plakalar arasındaki boşluğu kapatmaksızın durdurabilecek bir duvar yapısı bulabilmektir. Bu amaçla, değişken yanal periyodik profile sahip birçok dalga kılavuzu üretildi ve iletim ölçümleri için gerekli düzenek kuruldu.

Mikrodalga iletiminin, dalga kılavuzunun periyodik olarak oluklu iki plakasının birbirine göre bağıl pozisyonuna bağlı olduğu gösterildi. İletim bir plakanın diğerine göre oluğun yarım periyodu kadar kaydırılmasıyla sıfırdan maksimum değere kadar değişmektedir. Deneysel sonuçlar, plakalardan birisinin kaydırılmasıyla oluşan ve bant yapılı spektrumdan bantsız yapıya geçişe neden olan geometri bağımlı spektrum dönüşümü teorik öngörüsünü doğrulamıştır.

Anahtar Kelimeler: Düzlemsel dalga kılavuzu, elektromanyetik dalga, periyodiklik, Bragg yansıması.

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I'd like to express my gratitude to my supervisor Prof. Dr. Victor Pogrebnyak, the person who inspired me to acquire the necessary enthusiasm for this research. I would like to thank to the head of the department, Prof. Dr. Süleyman Güngör whom I took M.Sc. lectures and also had supplied me the necessary conditions to research. Also Asst. Prof. Dr. Turgut İkiz whom I took many lectures and learned many things in my B.Sc. and M.Sc. education. I also would like to thank Ömer Evren İnan, my friend and my colleague; we did many measurements with him during the time of research of this project. Also I would like to thank to Eser Akray for his friendship and assistance with measurements during the research of this thesis.

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1. INTRODUCTION

1.1 Bragg Reflection Phenomenon

Wave propagation in periodic media involves the behavior of waves with time, as the wave travels through a structure whose properties vary with position. It is the interaction of the time nature of the wave and the spatial nature of the medium that makes this situation unique.

The investigation of electromagnetic wave propagation in periodic structures is a topical problem in many fields of electronic technology such as optoelectronics for communication systems, photonic crystals, fiber and integrated optics, lasers, acoustic electronics, and many others. The principal physical property of wave propagation in a periodic structure, which lies in the basis of the performance of many devices, is the Bragg reflection phenomenon resulting in the Bragg photonic band gap (forbidden gap in the frequency spectrum). Fig. 1.1 illustrates this phenomenon in a simple periodic layered structure consisting of alternating layers with different dielectric constants ε_1 and ε_2 .

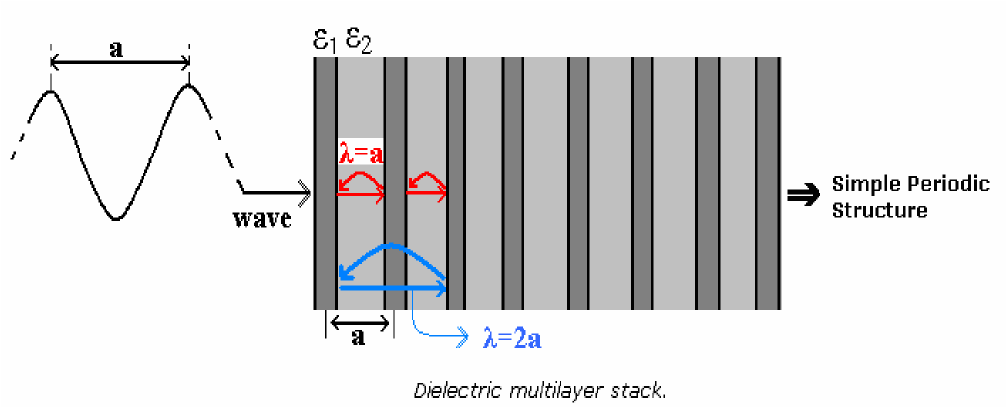


Fig. 1.1 The phenomenon in a simple periodic layered structure.

The Bragg reflection occurs both in the case of unbounded periodic medium as well as in a case of a bounded periodic structure like a periodic electromagnetic waveguide. Moreover, in the both cases the Bragg reflection arises at one and the same condition known as Bragg's law. Bragg's law is the mathematical formulation of the constructive interference of waves traveling along the axis of the periodic waveguide

In this thesis wave phenomena in a planar and a rectangular periodically corrugated waveguide investigated. A waveguide made of a dielectric layer located between metal plates is considered. The plates have a periodic uneven shape defined, for example, by the cosine function, amplitude of which is smaller than the thickness of the layer. The latter condition allows simplifying the solution of the problem by using the perturbation method. In such a waveguide, each mode given consists of superposition of space harmonics represented by the Fourier series. Thus, electromagnetic field in the waveguide is a sum of different harmonics, each of which is specified by a discrete transverse wave number (describing transverse modes) and another quasi-discrete longitudinal wave number (determining the wave traveling along waveguide).

It is known that the corrugation causes resonant interaction between the transverse modes. The width of the Bragg gap depends on the relative position of two periodic plates. It varies from zero to a maximum value upon shifting of one periodic plate with respect to another on the half period of the corrugation. When a frequency of the electromagnetic wave coincides with one of the gaps, only unidirectional propagation along grooves is allowed in the waveguide. Thus the shift of the plates switches the two-dimensional guiding structure to the unidirectional guide and creates the photonic stripe phase in such a periodic waveguide.

Bragg reflection or Bragg resonance is caused by periodicity. It is a forbidden gap in the electromagnetic spectrum of the periodic structure. The forbidden gap in the spectrum depends on the distance between the thickness and the phase shift of the waveguide. If the frequency of the wave coincides with Bragg-gap frequency the resonant wave can propagate only the opposite direction (reflection). This phenomenon is similar to that of the semiconductors band gaps. This is the interesting part for scientists.

In this thesis, the theoretical and the experimental works performed for planar periodically corrugated, rectangular periodically corrugated and planar periodically crossed corrugated waveguides. And microwave transmission through periodically corrugated waveguides was investigated. The results can be used for designing microwave filters, switchers, antennas and also for designing microwave photonic crystals with a very wide range of applications.

We experimentally proved that the results for Bragg phenomenon and the other theoretical results that have been calculated are one-to-one matched through all kind of periodic structures.

1.2 Publications Related to the Results of the Thesis

a) Journals:

1. V.A. Pogrebnyak, E. Akray, **A.N. Küçükaltun**, “Tunable gap in the transmission spectrum of a periodic waveguide”, **Applied Physics Letters**, vol. 86, 151115, 2005.

b) International Conferences:

1. V.A. Pogrebnyak, J.J Whalen, **A.N. Küçükaltun**, K.Bargach, “Tunable Microwave Transmission in Periodically Corrugated Waveguide”, Proceeding of 12th International Symposium on Antennas and Electromagnetics, 16-19 July 2006, University of Manitoba, Winnipeg, Manitoba, Canada, 2006.
2. V.A. Pogrebnyak, E. Akray, **A.N. Küçükaltun**, “Tunable microwave transmission spectrum in periodically corrugated waveguide”, the Proceedings International Loughborough Antennas & Propagation Conference (LAPC), pp. 289-292, 11-12 April, 2006, Loughborough University, Loughborough , UK
3. V.A. Pogrebnyak, J.J Whalen, **A.N. Küçükaltun**, K.Bargach, “Tunable Bragg gap in Periodic Waveguide, International Union of Radio Science, Book of Abstracts of the USA National Radio Science meeting, 4-7 January 2006, University of Colorado at Boulder, Boulder, Colorado, 2006.
4. V.A. Pogrebnyak, **A.N. Küçükaltun**, "Tunable Periodically Corrugated Waveguide as a Filter for Microwave Frequencies", Proceedings of the

International Conference in Physics/23rd Natl. Meeting of Turkish Physical Society devoted to Intl Year of Physics13-16 September 2005, Muğla University, p1446 - 1449, Muğla, Turkey, 2005.

5. V.A. Pogrebnyak, E. Akray, **A.N. Küçükaltun**, "Tunable electron transport in the lateral nanostructure", Proceedings of 2005 NSTI Nanotechnology Conference & Trade Show, 8-13 May 2005, Anaheim, California, vol. 3, pp. 61-63, Nano Science Technology Institute, U.S.A. 2005.
6. V.A. Pogrebnyak, U.Hasar, M.Güler, Ö.E.İnan, T.Eraslan, **A.N.Küçükaltun**, "Periodic Waveguide as a Frequency Selective Microwave Power Switch". p.116, Euro 2004- Electromagnetics Conference, Magdeburg, Germany, 2004.

c) National Conferences:

1. V.A. Pogrebnyak, Ö.E.Inan, U. Hasar, **A.N.Küçükaltun**, T.Eraslan, E. Akray, S Meral, "Periyodik olarak oluklu dalga kılavuzunun spektrumunda durdurma bantları".(Stop bands in the spectrum of a periodically corrugated waveguide) URSI Turkish Conference, Bilkent Üniversitesi, Ankara, Türkiye, pp. 48-50, 2004.
2. V.A. Pogrebnyak, **A.N. Küçükaltun**, E.Akray, "Ayarlanabilir mikrodalga filtresi olarak periyodik oluklu dalga kılavuzu", 1.RF ve Mikrodalga Ölçümleri Ulusal Çalıştayı (1.RFMD_UÇ),TÜBİTAK Ulusal Metroloji Enstitüsü, Gebze, Kocaeli, Türkiye, 26-28 Eylül, 2005.

d) Participated Projects

1. TUBITAK Project No: 101E045, Periyodik Yapıda Non-Bragg Fotonik Bant Aralığı, 2002-2004.
2. Project No: MMF 2004 BAP5, Periyodik Yapılarda Non-Bragg Durdurma Bantları, 2004-2006.

1.3 Previous Studies

Periodic systems are applied when it is desired to reduce the phase velocity of transmission-line waves. Commonly these systems consist of a set of uniformly spaced identical obstacles such as irises, metallic or dielectric cylinders or other arbitrary shaped posts. Slow waves are required for linear accelerators, delay lines, beam-interaction devices, radars, antenna feed systems and other microwave devices. Another example of periodic structures is artificial dielectrics and diffraction gratings. All the periodic structures are distinguished by existence of separated pass-bands and stop-bands. Rectangular corrugated waveguides have been a subject of interest to microwave and antenna engineers for three decades because of applications in diplexers, polarizers, filters and horns. The lack of a convenient model to analyze the modal fields for such devices has limited their applications and restricted the development of efficient design procedures. Simplified models based on the representation of the effect of the corrugations by impedance, lead to a set of inconsistent equations, according to Dybdal *et al*., and produce results that depart considerably from the actual behavior of the waveguide. More rigorous methods of analysis, for rectangular corrugated horns with plain corrugations were formulated by Khiin *et al*. These methods applied mode-matching techniques to the determination of the scattering matrix of the horn. The fields are expressed as an expansion over the modal fields for a smooth-walled rectangular waveguide, without an identification of the modes for the corrugated structure.

The dispersion properties and the fields of electromagnetic waves are investigated for propagation in a stratified infinite medium. The stratification is characterized by a dielectric constant which, along one coordinate, is modulated sinusoidally about an average value. A systematic and comprehensive study is presented for the case of H modes for which the pertinent wave equation is in the form of a Mathieu differential equation. The modes and dispersion characteristics are analyzed in terms of a "stability" chart, which is customary in the study of the Mathieu equation. Results are obtained for an unbounded medium and for a waveguide filled with the modulated medium. Also, the reflection occurring at an interface between free space and a semi-infinite medium of this type is examined. In addition to these rigorous results for arbitrary values of modulation, simple analytical expressions are given for all of these cases where the modulation in the dielectric is small. It is shown that the fields are then expressible in terms of the fundamental and the two nearest space harmonics. The fields within a unit cell in the stratified medium are calculated for both small and large modulation and for frequencies up through the second pass band. It is of interest that the variation of the fields is not, in general, simply related to the variation of the dielectric constant within a cell. Microcavities, photonic band-gaps and applications to lasers and optical communications are mentioned by Lee, R.K., Xu, Y. and Yariv, A.

J. A. Richards gives the description and classification of the differential equations with periodically varying coefficients in his book. And he also proposed various methods of solution to these types of equations. In the last chapter, some of the systems, in the analysis of which we should apply for the solution of these differential equations, are involved. The features of periodically time-varying systems, which are of major importance from an applications view point, are outlined. Allan R. Kaurs described a method for providing continuous mechanical tuning of a resonant dielectric ring filter for use with rectangular dielectric waveguide integrated circuits. The ability to mechanically tune a bandpass ring filter by varying the air gap beneath the structure provides for a continuously tunable filter for use with dielectric waveguide integrated circuits. This device could be used as a tunable preselector filter for the front end of a microwave receiver. It also provides a method for controlling the dependence of the filter response on the gap effect by providing a fine-tuning mechanism when fixed-frequency operation is desired.

Roland Gesche, *et al.* investigated two metallic or lossy dielectric cylinders placed in one cross section of a rectangular waveguide by means of the orthogonal expansion method. Resonances are shown by frequency responses of the transmission coefficient. They are discussed by patterns of the magnetic field and diagrams of the Poynting vector. Physical explanations of the resonances are given. They concluded that, the structure may be used as a filter element. With two small dielectric posts, a frequency characteristic with two stop-bands can be obtained. Center frequencies are tunable by moving the posts. Using one large metallic and one small dielectric post, a tunable pass-band characteristic can be realized. Results are given for some examples of filter elements. With two dielectric posts, two bandstop resonances occur. Furthermore, a tunable passband characteristic can be obtained with one large metallic and one small dielectric post.

Mode interaction in a slab waveguide with a periodically irregular boundary was studied in detail by V. A. Pogrebnyak. An electromagnetic standing wave resonance, is predicted in such a structure. The resonance is caused by the interaction of modes of different space harmonics. The resonance interaction results in spectrum splitting and in the appearance of forbidden gaps (stop-bands). In this connection the waveguide spectrum takes miniband character with densely spaced stopbands. Different spectrum features change significantly the electromagnetic properties of the waveguide. Thus, the derived theoretical investigation shows, while an electromagnetic wave traveling in the layer with a periodically irregular boundary, the standing wave resonances of modes of different space harmonics appear in the structure. The resonances cause the miniband behavior of the waveguide spectrum. The quantized electronic states of a particle whose motion is bounded in one direction by an uneven, impenetrable wall were investigated theoretically by V. A. Pogrebnyak, V. M. Yakovenko, and I. V. Yakovenko. It is shown that under certain conditions the presence of either a periodically uneven surface or a rough surface can give rise to surface states (caused by unevenness) whose wave functions decay exponentially with distance from the wall.

S. M. Tun, applied two different rectangular mode matching methods to the design of corrugated waveguide filters and polarisers with reduced width corrugations. The basic building block used in his analysis consists of a short rectangular or square waveguide with corrugations on the side walls. In his research, two different mode matching methods are described. The first is based on the matching of transverse TE and TM modes of a rectangular waveguide to those of a cross shape waveguide, in the second method the generalized scattering matrix of the a 3D rectangular cavity cell is evaluated. Both the transverse mode matching method and 3D cell mode matching method generally yield accurate results for the electromagnetic modelling of corrugated waveguide structures. However the 3D cell mode matching method exhibits better convergence behaviour over the transverse method. It also allows for the modelling of more complicated rectangular waveguide devices.

The dispersion properties and the fields of electromagnetic waves were investigated for propagation in a stratified infinite medium by T. Tamir *et al*. The stratification is characterized by a dielectric constant, which, along one coordinate is modulated sinusoidally about an average value. A systematic and comprehensive study is presented for the case of H modes for which the pertinent wave equation is in the form of a Mathieu differential equation. The modes and dispersion characteristics are analyzed in terms of a "stability" chart, which is customary in the study of the Mathieu equation. Results are obtained for an unbounded medium and for a waveguide filled with the modulated medium. Also the reflection occurring at an interface between free space and a semi-infinite medium of this type is examined, in addition to these rigorous results for arbitrary values of modulation, simple analytical expressions are given for all of these cases where the modulation in the dielectric is small. It is shown that the fields are then expressible in terms of the fundamental and the two nearest space harmonics. The fields within a unit cell in the stratified medium are calculated for both small and large modulation and for frequencies up through the second pass band. It is of interest that the variation of the fields is not, in general, simply related to the variation of the dielectric constant within a cell.

Edward E. Altshuler, investigated the propagation characteristics of a rectangular waveguide loaded with uniformly spaced cylindrical posts (periodic structure). He showed that the presence of the posts reduces the guide wavelength of the waveguide and the propagation characteristics of a rectangular waveguide are modified when the guide is loaded with uniformly spaced posts. A different approach was introduced by Navarro *et al*. that modeled a rectangular corrugated waveguide with plain corrugations by means of a cascade of identical multiport reactances connected by a finite number of uncoupled transmission lines. The fields were only expanded into LSE modes, which impose a limitation to the model. A. A. Maragos *et al.* studied the dispersion characteristics of a rectangular waveguide grating for microwave amplifier applications. The Floquet theorem and an appropriate standing waves expansion is employed to express the fields in the vacuum region and inside the grooves, respectively.

The application of the boundary conditions leads to an infinite system of equations, which is solved numerically by truncation. The main advantage of the procedure employed is that it gives directly and with a few spatial harmonics the dispersion relation. Amiya Kumar Mallick and Gitindra S, Sanyal investigated the wave propagation along a rectangular waveguide with slowly varying width. And also gives the results of the theoretical and experimental investigations on wave propagation through a rectangular waveguide having sinusoidally varying width along the axial direction. Mikio Tsuji and Soichi Matsumoto investigated a planar dielectric waveguide having finite periodic rectangular corrugation analytically and experimentally, in case of surface waves propagating at an angle to the corrugation. In analytical considerations, a finitely corrugated guide is regarded as consisting of many step discontinuities connected by a length of uniform slab waveguide, and its propagation characteristics in the Bragg interaction region are derived from a cascaded connection of the transmission matrix expressing a step discontinuity. Kazui-Hko Ogusu, have been measured the dispersion characteristics and the field distributions in rectangular-dielectric waveguides and in single material fibers at X-band frequencies to verify the validity of the analysis. Measured and calculated results shows that the analysis is useful to study the transmission characteristics of dielectric waveguides. The purpose is to determine experimentally the dispersion characteristics and the field distributions in rectangular-dielectric waveguides, cladded rectangular-dielectric waveguides.

Kawthar A. Zaki and Ali E. Atia described an accurate design technique of dual-mode microwave dielectric or air-filled rectangular waveguide filters. Dual-mode coupling is realized by a section of rectangular waveguide with square-corner-cut. The filters are based on evanescent mode waveguides to realize an unequal coupling pair between adjacent dual-mode cavities and comer-cut waveguide for dual-mode coupling. George Goussetis and Djuradj Budimir proposed a novel ridged waveguide band-pass filter configuration. The proposed filter has comparable size to standard E-plane filters while having suppressed spurious resonance. Compactness is achieved taking advantage of the properties of slow waves in half wavelength resonators, while spurious behavior suppression is achieved by means of an integrated low-pass structure. Periodicity is readily imposed upon cascading ridge waveguide with rectangular waveguide.

In Sander and Reed's book, the existence and properties of waves guided by conductors, either in the form of two-conductor systems or of hollow tubes investigated. And also the type of structures that support TEM waves investigated. Systems of two or more perfect conductors embedded in a homogenous dielectric medium and which have an axis of uniformity will support a principal wave in which the electric and magnetic fields are orthogonal and are transverse to the axis of uniformity. Such a wave is propagated with the velocity of a uniform plane wave in the unbounded dielectric medium. In any given plane perpendicular to the axis a unique voltage and current may be defined. Inside a hollow tube no principal wave exists: it is necessary to have an axial component of either *E* or *H*. modes are designated transverse magnetic (*TM*) transverse electric (*TE*). Each mode has its own field pattern and is characterized by a particular cut-off frequency. Propagation of a mode occurs only for frequencies exceeding the cut-off frequency of that mode. Below the cut-off frequency the mode is evanescent. Modes are nominally independent. The characteristics of a single mode can be translated into an equivalent transmission line. Henry J. Stalzer *et al.* numerically calculated the cutoff frequencies and modal fields of dually polarized crossed rectangular waveguide and verified the cutoff frequencies experimentally. And they used symmetry arguments and group theory in order to explain mode degeneracies and mode splitting. The cutoff frequencies and transverse field patterns of the first five modes are obtained numerically using the triangular finite element method.

Gennadiy I. Zaginaylov *et al*. studied for the first time in the rigorous mathematical manner the dispersion characteristics of the rectangular waveguide grating for microwave amplifier applications on the basis of singular integral equation (SIE) method. In the paper: full-wave modal analysis of the rectangular waveguide grating. Numerical results show that the dispersion curves obtained by the

SIE method are in surprisingly good agreement with those obtained before. Additionally, it has been pointed out that there exists some regime where the differences between the SIE and simplified treatments become notable. Investigation of the EM properties for various structures starts from the formulation of the related boundary value problem for the Maxwell equations.

For numerous types of electrodynamic structures, it can be reduced identically (without any simplified assumptions) to a certain integral equation. The dimension of the related integral equation is less than that for the initial boundary value problem. Until recently, some inconvenience of such a methodology was associated with the numerical analysis of the integral equation. Such an integral equation is, as a rule, the first kind and contains singularities in the kernel. A solution to this kind of integral equation is fairly unstable for small perturbations. Because of this instability, the direct numerical analysis for the case in hand does not seem to be efficient. Meanwhile, the traditional regularization results in the integral equation of the second kind, but with a much more complex kernel, although it requires a great amount of additional analytical procedures. The more notable difference between SMA and SIE approaches should be expected in the scope of the linear and, especially, nonlinear analysis of the corresponding structure with the electron beam, since the process of beam bunching responsible for the beam–wave instability is more sensitive to the local field behavior than it is to the dispersion properties of the "cold" structure. Periodic gratings on rectangular dielectric image guide operating in their first stop bands (Bragg reflection) have been proposed as millimeter-wave filter components which produce strong reflections with negligible radiation.

M. J. Shiau *et al*. show that mode conversion effects occur which produce additional stop bands that may affect device performance. Although open dielectric waveguides, such as the rectangular dielectric image line, the insular line, and the inverted strip line, seem very promising for use at millimeter wavelengths, particularly at the higher frequencies, problems remain in connection with components in such waveguides. Because of the open nature of these guides, one must avoid sharp discontinuity structures that give rise to unwanted radiation. For this reason, they suggested that components such as filters and resonators be designed employing periodic gratings placed on top of the dielectric waveguide. Such gratings would be operated in their stop bands, corresponding to Bragg reflection, in order to produce strong reflections with negligible radiation. The multiplicity of stop bands appearing in the dispersion curves indicates that problems can arise in the use of gratings to produce filter components in open dielectric waveguides. There are two sources of difficulty: (a) the proximity of neighboring stop bands, and (b) the mode-conversion (polarization conversion) effects. These sources of difficulty and how they manifest themselves in specific device contexts must be better understood before filters or other components can be reliably designed.

J. Rodriguez *et al*. have applied the procedure for analysing periodical structures and waveguide photonic crystals in planar optical waveguides with different lattice constants. They show the efficiency of a procedure for obtaining the complete electromagnetic scattering caused by single and multiple abrupt discontinuities in dielectric waveguides with arbitrary cross section shape and any refraction index profile functions. This method is focused on a new concept of the Generalized Scattering Matrix Method (GSMM**)**. In order to obtain the Generalized Scattering Matrix (GSM) of any cascaded set of abrupt discontinuities, the Generalized Telegraphy's Equations (GTE) formulation and the Modal Matching Technique (MMT) were extended to work at optical frequencies. Multiple discontinuities in planar optical waveguides were analysed and numerical results for complex scattering coefficients are given. Gradual and abrupt transitions between cylindrical dielectric waveguides were evaluated experimentally. The method makes possible the analysis of optical devices such as: gradual transitions, segmented optical waveguides, optical waveguide gratings, waveguide periodical configurations, as well as waveguide photonic band gaps nanostructures. The method combines the MMT technique with the GSM concept, resulting in a successful and powerful tool to evaluate the electromagnetic scattering caused by abrupt discontinuities between dielectric waveguides. The procedure has demonstrated the possibility of designing very simple and low cost microwave devices, such as: power dividers, filters, electromagnetic windows and resonators, At optical frequencies, it would be useful in the analysis and design of photonic devices in periodic waveguides, waveguide photonic crystals as well as optical interconnects. The rectangular dielectric waveguide and its modifications have been extensively studied because of their compatibility with integrated circuits.

Kazuhiko Ogusu, determine the field distribution for various kinds of dielectric waveguides to provide the basic knowledge of their physical properties using the generalized telegraphist's equations. Numerical results include dispersion characteristics, lines of force, and equicontours of the electromagnetic power density. In the research, the rectangular dielectric image line, the cladded rectangular dielectric imageline, the insulated image guide, and the strip dielectric guide treated. The numerical results include the dispersion characteristics, the lines of force, and the power distribution. It is shown that the analysis can give good results even for open dielectric waveguides with arbitrary dielectric profiles and cross sections even though the analysis is based on a closed waveguide model. The results can be useful to understand the wave propagation in these dielectric waveguides.

With the development of low-loss, high-dielectric constant materials, a new type of waveguide transmission line offers advantages in bandwidth and power handling capacity over conventional waveguides. P. H. Vartanian *et al.*, investigated the propagation in dielectric loaded rectangular waveguide theoretically for varying slab thickness and dielectric constant. The slabs are placed across the center of the waveguide in the *E* plane. This geometry is found to offer bandwidths in excess of double that of rectangular waveguide for dielectrics having dielectric constants of approximately 18. Power handling capacities which are double or triple that of standard waveguide are achievable using the dielectric loaded waveguide. In addition to the theory, design curves of bandwidth, guide wavelength, cutoff wavelength, impedance, power handling capacity, wall losses, and dielectric losses are presented and compared to experiment where possible. Both the ridged and the dielectric loaded waveguides add capacitance to the dominant mode, while only slightly affecting the capacitance associated with the next higher mode. The dielectric loaded waveguide, unlike the ridged guide, does not reduce the air gap and, consequently, the power handling capacity, but instead adds material having a higher breakdown strength to the region where breakdown is most likely. Consequently, the power handling capacity is higher with the loaded waveguide.

The general results, if compared to ridged waveguide, are that the dielectric loaded waveguide is superior in every respect, with the assumption that suitably low-loss dielectric materials are available. The research theoretically investigates the propagation characteristics of the Te_{no} modes in dielectric loaded waveguide. The analysis yields design curves of bandwidth, guide wavelength, cutoff wavelength, impedance, power handling capacity, wall losses, and dielectric losses.

An open-ended rectangular waveguide, which is a typical form of radiating structure, has many practical applications in communication, radar, and medical systems as single or coupled radiators and has been studied extensively by a variety of methods. Hirohide Serizawa and Kohei Hongo studied the radiation from a rectangular waveguide with a perfectly conducting infinite flange is rigorously by using the method of the Kobayashi potential (KP). The fields in the waveguide and half-space are expanded in terms of the waveguide modes and the Weber–Schafheitlin discontinuous integrals, respectively. The earliest work on the flanged rectangular waveguide was accomplished by mainly using variational methods. The dominant waveguide mode was generally assumed as an aperture trial field and the cross polarization was neglected. The radiation from a perfectly conducting flanged rectangular waveguide has been rigorously formulated by means of the KP.

Recently, many authors have used an integral equation approach with the method of moments (MoM) or the mode matching method to investigate the behavior of the single and, particularly, coupled waveguides. Mailloux expanded the aperture field in a set of LSE modes and used a point-matching approach. In a second paper on the topic, the cross-polarized component was included, but a dominant mode approximation was applied (higher-order modes were included in part of the results). Hockham and Walker formulated the coupling of waveguides with an iris by using a set of orthogonal functions related to LSE modes and the asymptotic behavior of higher-order modes was studied in. Some authors applied the mode-matching method to finite arrays and all the TE and TM modes were considered. Bird obtained a general mutual admittance formula which has been applied to rectangular waveguide arrays of identical elements, and of different-sized elements. Kitchener *et al.* evaluated the mutual admittance using a Fourier representation of the Green's function, while Bird used Lewin's method to directly calculate the mode admittances. The generalized network formulation, which is based on the equivalence principle and the MoM, was applied to a waveguide with a thin window, reactively loaded waveguide arrays, and finite phased arrays. J. Luzwick and R. F. Harrington used the dominant waveguide mode and a sinusoidal aperture function, respectively.

A waveguide with a thick window was solved by B. N. Das *et al.*, but the cross polarization was neglected. Other methods have also been applied to flanged rectangular waveguides. MacPhie and Zaghloul used the correlation matrix method based on the energy conservation law, while Teodoridis *et al.* applied the method of characteristic modes which reduces the problem to eigenvalue equations. J. A. Encinar were considered two different methods based on the modal analysis, but the cross polarization was ignored. Baudrand *et al.* used the transverse operator method to obtain an integral equation that was solved by Galerkin's method. Methods based on the Fourier analysis and mode matching were applied to waveguides with a three-layered tissue and with a lossy flange. M. Mongiardo and T. Rozzi derived a rigorous variational solution of single and twin radiators by using a singular integral equation approach based on Galerkin's method with the Gegenbauer polynomials as basis functions and faster convergence was obtained. Rafal Lech and Jerzy Mazur analysed the propagation in periodically loaded waveguide structures and showed the existence of pass-bands and stop-bands, which are characteristic for periodic structures. They analyzed that the periodic structures containing the sections of cylindrical posts described by modal scattering matrix. The proposed procedure in their research allows determining the propagation constants of the Floquet modes from the classical eigenvalues of a characteristic matrix, determined from scattering matrix of the guide section. This method is more time-effective than solving the nonlinear determinant equation by an iterative process. Only the modal scattering matrix of a single section and the period are needed for the calculations.

With an axially magnetized cylindrical ferrite rod inserted into a rectangular waveguide parallel to the E-field of the dominant (TE_{10}) mode, the electromagnetic field amplitudes inside the ferrite rod and the transmission and reflection coefficients are numerically obtained by Toshio Yoshida *et al.* In their research the numerical results for the transmission and reflection coefficients and the amplitude of the field inside the rod are shown. Much fundamental information on these problems is obtained by studying the case of the waveguide containing a circular cylindrical ferrite rod inserted parallel to the *E* field of the dominant mode in a rectangular waveguide and axially magnetized by an external static magnetic field. An analysis of this situation was discussed first by Epstein and Berk. They successively introduced the scattered wave from the rod and the mirrored waves from the guide walls to satisfy the boundary conditions. However, it would not only be difficult but unfeasible to obtain an approximate solution of higher order than the first, because of its cumbersome nature. But in order to obtain more precisely the field distributions inside the rod and the transmission and reflection coefficients, we need the higher order approximate or rigorous solution. Okamoto et al. obtained the rigorous solution of this problem by taking account of an infinite number of images of the rod with respect to the guide walls. However, they did not give any results of numerical computation about the field distributions.

1.4 Electron Transport in Laterally Periodically Modulated Nanostructure: Analogy with Periodic Waveguide

The study of two-dimensional electronic systems evokes considerable interest due to the broad utilization of the systems in nanotechnology. Design of new devices is commonly based on exploiting the different configurations of multiple-quantum-well (MQW) structures. In these nanostructures, the vertical transport of electrons across quantum wells is commonly used. Despite great progress in this field, a MQW has one main inherent defect: a period of the structure is always greater than a thickness of a single quantum well. Therefore, the electron energy, associated with the period, is always less than the energy of the ground state in the single quantum well.

Taking into consideration that the energy level crossing causes important resonance properties of the system, it becomes clear that these resonant properties are excluded from MQW structures using the vertical transport. This defect can be avoided if the in-plane transport of electrons in a quantum well with periodic boundaries is used. In this case there are neither physical nor principal technological restrictions on the relationship between thickness and a period.

Modern technology can create lateral nanostructures with a modulation period up to a few nanometers. In this communication, we presented the theoretical investigation of the band structure of a periodically corrugated quantum well and experimental modeling of the well by the periodic microwave waveguide. It is shown that the lateral periodic corrugation allows controlling totally the in-plane electron transport in such quantum well.

For example, the electron transport varies from zero to a maximum value upon a shift of one periodic boundary with respect to another on the half period of the corrugation. This transformation corresponds to metal-insulator transition in the nanostructure that can not be observed in MQW structures using the vertical transport. The metal-insulator transition is caused by the opening of the gap in the energy band diagram of the nanostructure. De Broglie wavelength is:

$$\lambda = \frac{h}{p} \tag{4.1}$$

$$p = m\upsilon \tag{4.2}$$

Typical λ in semiconductor is 10-100 nm
$\upsilon_{electron}$ □ $10^5 - 10^6 m/\sec$

The de Broglie wavelength is given in the eq. 4.1, where λ is the particle's wavelength, h is Planck's constant, p is the particle's momentum, m is the particle's rest mass, υ is the particle's velocity.

The electron properties of the periodic well depend on a ratio between the de Broglie wavelength and characteristic dimensions of the well, therefore, the electron phenomena can be modeled by the periodic waveguide with the same ratio between the parameters. The principal condition of observation of the properties, caused by periodicity in the nanostructure, is l >> a, where l is the electron mean free path, and a is a period of the lateral modulation. The advantage of microwaves in such modeling is the very large “mean free path“ of the electromagnetic wave, almost matching the electron mean free path in superconductors. So the mentioned condition is always met. Figure 3.3 illustrates the experimental observation of microwave transmission (“metal-insulator transition”) through periodic waveguide

2. THEORETICAL INVESTIGATIONS

2.1. Electromagnetic Wave Propagation in a Planar Periodically Corrugated Waveguide with Movable Plates: Statement of the Problem

2.1.1.Geometry and Initial Equations

In this part, electromagnetic wave propagation through a periodically one dimensional corrugated waveguide has investigated. The source document of this theoretical part is the paper by Pogrebnyak (2003, 2004). In Figure 2.1. There is an open waveguide is shown with upper and lower boundaries, which are conductors.

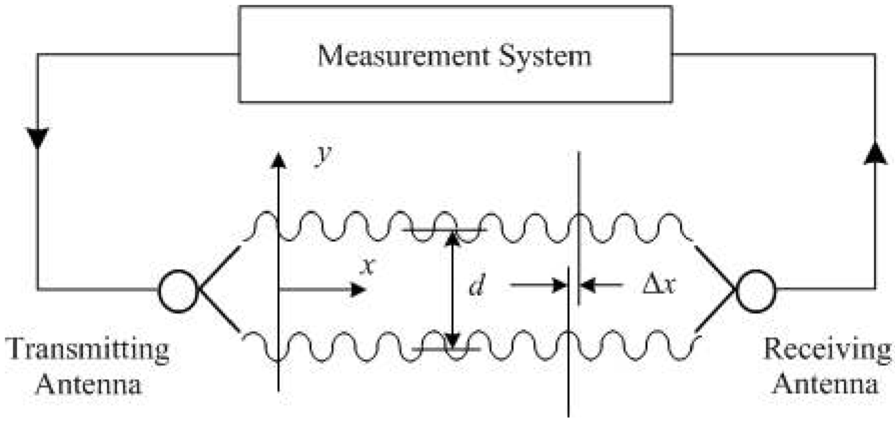


Fig. 2.1. Geometry of one dimensional planar periodically corrugated waveguide.

There is a dielectric medium which is assumed to be linear, homogeneous, isotropic and non-dispersive located between these conductor boundaries ($y_d(x) > y > y_{-d}(x)$). The profiles of these plates are sinusoidal functions. The notations that used in here are: ξ denotes the amplitudes of the upper and lower plate corrugation, and the plates' corresponding expressions for the profiles are $y_d(x) = d/2 + \xi\cos(qx + \Delta x)$ for upper plate and $y_{-d}(x) = -d/2 + \xi\cos(qx)$ for the lower one. In this geometry, $q = 2\pi/a$, and a is the period of the corrugations, d is average thickness between parallel plates and Δx is the phase shift between the parallel plates. We assumed that the corrugations' amplitudes are small i.e. $\xi/d \ll 1$ and $\xi q \ll 1$.

In source free and losses media, Maxwell's equations can be written in differential form such;

$$\nabla \times \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} \tag{2.1.1}$$

$$\nabla \times \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} \tag{2.1.2}$$

$$\nabla . \vec{D} = 0 \tag{2.1.3}$$

$$\nabla . \vec{B} = 0 \tag{2.1.4}$$

The first two Maxwell's equations are uncoupled, and the wave equations are obtained as follows;

$$\nabla^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} \tag{2.1.5}$$

$$\nabla^2 \vec{H} = \mu\varepsilon \frac{\partial^2 \vec{H}}{\partial t^2} \tag{2.1.6}$$

For time harmonic fields (time variations are of the form $e^{j\omega t}$), the wave equations can be written as;

$$\nabla^2 \vec{E} = -\omega^2 \mu\varepsilon \vec{E} = -k^2 \vec{E} \tag{2.1.7}$$

$$\nabla^2 \vec{H} = -\omega^2 \mu\varepsilon \vec{H} = -k^2 \vec{H} \tag{2.1.8}$$

In general, the wave equation can be written as;

$$\nabla^2 \varphi + k^2 \varphi = 0 \tag{2.1.9}$$

k can be written as in terms of ε, the electric permittivity of the medium, and c, velocity of light, as;

$$k^2 = \varepsilon \frac{\omega^2}{c^2} \tag{2.1.10}$$

and via explicit form of the Laplacian, the wave equation becomes in form;

$$\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}+\varepsilon\frac{\omega^2}{c^2}E=0 \qquad (2.1.11)$$

and wave equation supports the boundary condition in such equation;

$$E(x,y_{-d}(x))=E(x,y_d(x))=0 \qquad (2.1.12)$$

Where, ω is the wave frequency, ε is the dielectric constant of the medium, c is the velocity of light. $E(x,y)$ can be represented in Fourier Series (Floquet's Theorem) because of boundary periodicity.(We are able to ignore k_z because our wave propagates in x direction and it is assumed that there is no variation along the z direction)

$$E(x,y)=\sum_n [a_n\cos(k_{yn}y)+b_n\sin(k_{yn}y)]e^{j(k_x+nq)x} \qquad (2.1.13)$$

Where a_n and b_n are the Fourier series coefficients; k_{yn} is transverse component and k_x is the longitudinal components of the wave vector $\vec{k}$.

From the wave equation (2.1.11) and equation (2.1.13) we can reach such relation;

$$\varepsilon\frac{\omega^2}{c^2}-(k_x+nq)^2-k_{yn}{}^2=0 \qquad (2.1.14)$$

This relation is then used for finding of the dispersion relation, $\omega(\vec{k})$.

Via expressing equation (2.1.13) as a Mclaurin series at the boundaries, $y=-d/2$ and $y=d/2$, and then substituting of these equations into the boundary condition, we can reach a system of linear algebraic equations for the coefficients a_n and b_n. By solving the determinant of this system for zero, the allowed values of k_{yn} can be found, so the frequency spectrum of the waveguide can be found. For small corrugations, it is sufficient to take the first three space harmonics. It can be easily realized that a_n and b_n decrease when n increases. That's why we can restrict ourselves to the approximation of three main space harmonics with the wave numbers k_0 and $k_{\pm 1}$.

Regarding the approximations mentioned above, the terms including ξ with powers of order higher than 2 may be eliminated.

For $$E(x,y) = \sum_n [a_n \cos(k_{yn} y) + b_n \sin(k_{yn} y)] e^{j(k_x + nq)x},$$

Expressing $E(x,y)$ in Mclaurin series at $y = -d/2$ and $y = d/2$ gives;
For lower boundary,

$$\begin{aligned} E(x,y)(y=-d/2) = \sum_n \Bigg[& \left[a_n \cos(k_n \frac{d}{2}) - b_n \sin(k_n \frac{d}{2}) \right] e^{j(k_x+nq)x} \\ & + \left[a_n k_n \sin(k_n \frac{d}{2}) + b_n k_n \cos(k_n \frac{d}{2}) \right] \xi \cos(qx) e^{j(k_x+nq)x} \\ & + \left[-\frac{1}{2} a_n k_n^2 \cos(k_n \frac{d}{2}) + \frac{1}{2} b_n k_n^2 \sin(k_n \frac{d}{2}) \right] \xi^2 \cos^2(qx) e^{j(k_x+nq)x} \Bigg] \end{aligned} \tag{2.1.15}$$

And for upper boundary,

$$\begin{aligned} E(x,y)(y=d/2) = \sum_n \Bigg[& \left[a_n \cos(k_n \frac{d}{2}) + b_n \sin(k_n \frac{d}{2}) \right] e^{j(k_x+nq)x} \\ & + \left[-a_n k_n \sin(k_n \frac{d}{2}) + b_n k_n \cos(k_n \frac{d}{2}) \right] \xi \cos(qx + \Delta x) e^{j(k_x+nq)x} \\ & + \left[-\frac{1}{2} a_n k_n{}^2 \cos(k_n \frac{d}{2}) - \frac{1}{2} b_n k_n{}^2 \sin(k_n \frac{d}{2}) \right] \xi^2 \cos^2(qx + \Delta x)] e^{j(k_x+nq)x} \Bigg] \end{aligned} \tag{2.1.16}$$

At this stage we should restrict ourselves to main 3 harmonics of the wave and write 3 equations for equations (2.1.15) and (2.1.16), each harmonics corresponds to -1, 0, 1 values of n. This gives us the system of 6 algebraic equations which will lead us to analytic solution with a good approximation. Also, here two constraints should be taken into account. The first is, $\xi/d << 1$ which states the comparable size of amplitudes of the corrugations of the two plates with respect to the plate separation. The second is, $\xi/a << 1$, which gives the comparable size of the amplitudes of the corrugations with respect to the wavelengths of the corrugations. The next step is putting these six equations into a matrix form and pursuing the nontrivial solution.

Consequently, the following characteristic equation is obtained (Pogrebnyak, 2003, 2004) for determination of allowed values of k_{y0} in the first Brillouin minizone;

$$\tan(k_0 d) = \frac{1}{2}\xi^2\left[\left[\frac{k_0 k_1}{\tan(dk_1)} + \frac{k_0 k_{-1}}{\tan(dk_{-1})}\right] - \frac{\cos \Delta x}{\cos(k_0 d)}\left[\frac{k_0 k_1}{\sin(k_1 d)} + \frac{k_0 k_{-1}}{\sin(k_{-1} d)}\right]\right] \qquad (2.1.17)$$

where $k_{\pm 1}$ are the wave numbers of the $n = \pm 1$ harmonics.
From equation (2.1.14), we can obtain

$$k_{\pm 1} = \sqrt{k_0{}^2 \mp 2k_x q - q^2} \qquad (2.1.18)$$

In equations (2.1.17), (2.1.18) and below the subscript y is dropped in the wave number k_{yn}.

2.1.2 Band Structure of the Frequency Spectrum: Pass and Stop Bands

Phase shift phenomenon between parallel plates is investigated theoretically in this section. There are some physical differences between this event and the previous.

First of all, in this case k_x is not equal to zero, in fact here the resonance of the wave movement in the direction that is perpendicular to the wave propagation takes place, in other words interaction of partial standing wave resonance between $n=0$ and the neighboring $n=\pm 1$ space harmonics is observed.

It is seen from equations (2.1.17), that resonance (stop band) in the system occurs if;

$$k_{\pm 1} = \sqrt{k_0{}^2 \mp 2k_x q - q^2} = \frac{m\pi}{d} \equiv k_{1m},\ m = 1,2,3,..... \tag{2.1.19}$$

An index m designates the order number of the resonance in the system and it can be considered as the “mode” index of the $n=\pm 1$ space harmonics but in the resonance case only. From equation (2.1.19), it is seen that $m \le p$ for the first minizone.

The Bragg resonance, $k_{x,B}^{\pm} = \pm q/2$, is a particular case of equation (2.1.19) at $m = p$. Number of resonances equal order number of the mode. For example, there are two resonances in the spectrum of the second mode ($p = 2$).

The physical meaning of the resonance (stop band) condition becomes clear if the last equations are rewritten in terms of a wavelength ($\lambda = \frac{2\pi}{k}$) of standing-wave associated with the transverse modes ($k_0^{(0)}$ and $k_{\pm 1}$) of the fundamental ($n=0$) and the $n=\pm 1$ space harmonics.

$$k_{\pm 1} = \frac{m\pi}{d} = \frac{2\pi}{\lambda} \Rightarrow d = \frac{m\lambda}{2} \tag{2.1.20}$$

$$k_0^{(0)} = \frac{p\pi}{d} = \frac{2\pi}{\lambda} \Rightarrow d = \frac{p\lambda}{2} \tag{2.1.21}$$

$$d = \frac{p\lambda_0}{2} = \frac{m\lambda_1}{2} \tag{2.1.22}$$

Equation (2.1.22) shows that the resonance occurs if the thickness of the waveguide, d, is simultaneously a multiple of half wavelengths of the standing-waves associated with the fundamental ($n = 0$) and the $n = \pm 1$ space harmonics but with different integers p and m. It is illustrated with Figure 2.2 where TE_{01} and TE_{02} field distributions for resonance cases are shown. In Figure 2.2, wave movement in the direction that is perpendicular to the wave propagation is shown as E_z.

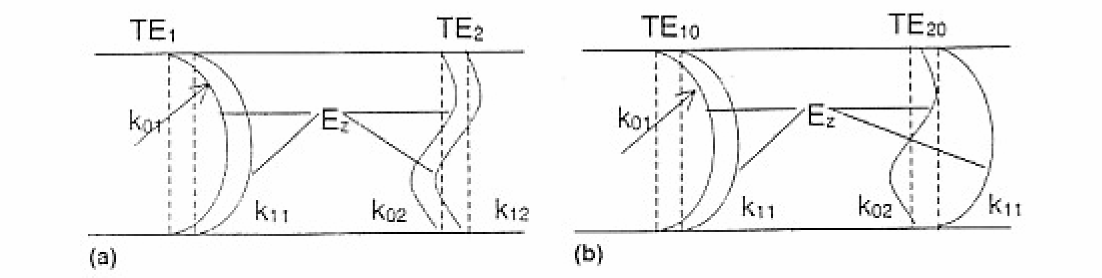


Fig. 2.2. Electric field distributions for the fundamental, k_{0p}, and the first, k_{1m}, space harmonics of the TE_{10} and TE_{20} waves. (a) In a case of the Bragg resonance, distributions for both harmonics are always similar; (b) TE_{20} has different field distributions for the harmonics (Pogrebnyak, 2003, 2004)

It is suitable to underline here that in contrast to common consideration of interference of longitudinal traveling waves that gives rise to the Bragg reflection, equations (2.1.19), (2.1.22) are the conditions of the constructive or destructive interference of the transverse modes (standing-waves).

The resonant value $k^{\pm}_{x,p,m}$ of the wave number k_x, at which the resonance condition (2.1.19)-(2.1.22) holds, can be found from equations (2.1.14) and (2.1.19);

$$\frac{m^2\pi^2}{d^2} = \frac{p^2\pi^2}{d^2} \mp 2k_x^{\pm}q - q^2 \tag{2.1.23}$$

$$k_x^{\pm} = \frac{(p^2 - m^2)\pi^2}{2qd^2} - \frac{q}{2} \tag{2.1.24}$$

$$k_{x,p,m}^{\pm} = \pm \frac{1}{2q}(k_{0p}^2 - q^2 - k_{1m}^2) \quad (2.1.25)$$

The upper sign "+" is taken for the resonant $n = +1$ harmonic and the "-" lower for the $n = -1$ harmonic. In equation (2.1.26), it is enough to consider the range $k_x > 0$ since it is obvious that;

$$k_{+1}(-|k_x|) = k_{-1}(|k_x|)$$

2.1.3. Spectrum of Subminizones

We can obtain the resonant frequency with substituting of $k_{x,p,m}^{\pm}$ into equation (2.1.14);

$$\varepsilon \frac{\omega^2}{c^2} - (k_x + nq)^2 - k_{yn} - k_z = 0 \quad (2.1.14)$$

As we know $k_z = 0$. So equation (2.1.14) becomes;

$$\varepsilon \frac{\omega^2}{c^2} - (k_x + nq)^2 - k_{yn} = 0$$

If we substitute $n = 0$ in above equation;

$$\omega^2 = \frac{c^2}{\varepsilon}(k_{x,p,m}{}^2 + k_{0p}^2)$$

$$\omega_{pm} = \frac{c}{\sqrt{\varepsilon}} \left[k_{0p}^2 + \left(\frac{k_{0p}^2 - q^2 - k_{1m}^2}{2q} \right)^2 \right]^{1/2} \quad (2.1.26)$$

In vicinity of resonance, the more accurate solution of equation (2.1.17) shows that this resonant frequency splits into two values as ω_{pm}^{+} and ω_{pm}^{-}. And these two values are separated by the forbidden gap $\delta\omega_{pm}$. To reach more accurate solution of resonant frequencies and stop band, below procedures are done;

$$k_{\pm 1} = \frac{m\pi}{d},\ m = 1, 2, 3, ... \tag{2.1.27}$$

$$k_0 = k_0^{(0)} + \delta k = \frac{p\pi}{d} + \delta k \tag{2.1.28}$$

From equations (2.1.14) and (2.1.19)

$$k_{\pm 1} = \sqrt{\frac{p^2\pi^2}{d^2} \pm 2k_x q - q^2} \tag{2.1.29}$$

and

$$k_{x,p,m}^{\pm} = \pm\frac{q}{2}(1 + X_{p,m}) \text{ where } X_{p,m} = \frac{(m^2 - p^2)\pi^2}{(dq)^2} \tag{2.1.30}$$

Then

$$\omega_{p,m}^{\pm} = \omega_{p,m} \pm \frac{c^2}{\varepsilon}\frac{p\pi^2}{d^3}\frac{m\xi}{\omega_{p,m}}\left[1 + (-1)^{p-m+1}\cos\Delta x\right]^{1/2} \tag{2.1.31}$$

$$\omega_{p,m}^{\pm} = \omega_{p,m}\left[1 \pm \sqrt{2}\,\frac{\xi}{d}\frac{\omega_{0p}\omega_{1m}}{\omega^2_{p,m}}\left[1 + (-1)^{p-m+1}\cos\Delta x\right]^{1/2}\right] \tag{2.1.32}$$

And the stop band appears as;

$$\delta\omega = \omega_{p,m}^{+} - \omega_{p,m}^{-} = 2\sqrt{2}\,\frac{\xi}{d}\frac{\omega_{0p}\omega_{1m}}{\omega_{p,m}}[1 + (-1)^{p-m+1}\cos\Delta x]^{1/2} \tag{2.1.33}$$

where

$$\omega_{0p} = \frac{ck_{0p}}{\sqrt{\varepsilon}}, \ \omega_{1m} = \frac{ck_{1m}}{\sqrt{\varepsilon}} \tag{2.1.34}$$

Thus, the resonances divide the first minizone of the p th mode into subminizones. The index m shows the order number of the subminizone. A number of subminizones can be found from relation (2.1.19). Since the last gap (Bragg) takes place at $m = p$, it means that a number of subminizones equals the order number of the mode p. The number of subminizones is the same as a number of gaps, including the Bragg gap. For example, there are two subminizones in the spectrum of the second mode (p =2).

The dispersion curve for this case is shown in Figure 2.3. The right side of the graph represents dispersions for the symmetric waveguide ($\Delta x = a/2$), the left for the asymmetric waveguide ($\Delta x = 0$). The dispersion for the *TE01* mode, investigated in the experiment, is shown by the thick line. The range, $\Delta k_{x,m}$, between two successive resonances in the k-space can be found from equation (2.1.25).

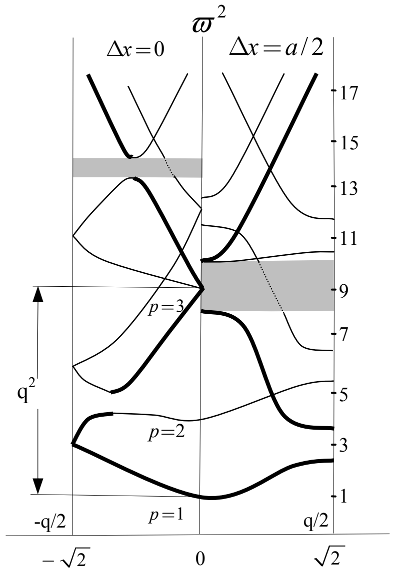


Fig.2.3. Dispersion $\varpi^2(\kappa)$ for the periodic waveguide with the chosen dimensions. Here $\varpi = \omega/(ck_{01})$, $\kappa = k_x/k_{01}$, $q = q/k_{01}$, $k_{01} = \pi/d$. The right side of the graph represents dispersions for the symmetric waveguide ($\Delta x = a/2$), the left for the asymmetric waveguide ($\Delta x = 0$). The dispersion for the *TE01* mode, investigated in the experiment, is shown by the thick line.

$$\Delta k_{x,m} = k^{+}_{x,p,m+1} - k^{+}_{x,p,m} = \frac{2m+1}{2q}\frac{\pi^2}{d^2} \tag{2.1.35}$$

It does not depend on the mode index p.

From equation (2.1.26) it is seen that the resonant frequency approaches to the cutoff frequency in parenthesis $(k_{0p}^2 - q^2 - k_{1m}^2)$ vanishes. Equality of this expressions to zero imposes relationship between a thickness and a period of the waveguide and mode indices p and m. It means that given cutoff frequency will be resonant under the specific geometric relationship. That is why the resonance can be named as the geometric resonance.

2.1.4. Effect of the Phase Shift between Parallel Plates on Wave Transmission

In this section of theoretical investigations, it is shown that dependency of bandwidth of the stop band on the phase shift between parallel plates. The analysis of equations (2.1.32), (2.1.33) is given here in such two cases:

(1) Case for $\Delta x = 0$,

(2) Case for $\Delta x = \pi$

1) Case for Asymmetric Waveguide $\Delta x = 0$:

In this case, the distance between two boundaries is constant and equals to d throughout the x-coordinate.

(a) If both p and m are even or both are odd numbers, the equations (2.1.32), and (2.1.33) for the resonant frequency and the stop band becomes;

$$\omega^{\pm}_{pm} = \omega_{0p} \tag{2.1.36}$$

$$\delta\omega_{pm} = \omega^{+}{}_{0p} - \omega^{-}{}_{0p} = 0 \tag{2.1.37}$$

(b) If p is even but m is odd or vice versa;

$$\omega_{pm}^{\pm} = \left[1 \pm 2\frac{\xi}{d_r}\frac{m}{p}\right]\omega_{0p} \tag{2.1.38}$$

$$\delta\omega^{\pm}{}_{pm} = \omega^{+}{}_{0p} - \omega^{-}{}_{0p} = 4\frac{\xi}{d_r}\frac{m}{p} \tag{2.1.39}$$

2) Case for Symmetric Waveguide $\Delta x = \pi$:

In this case, distance between parallel plates varies with the x-coordinate between values $d+\xi$ and $d-\xi$.

(a) If both p and m are even or both are odd numbers, the equations for the resonant frequency and pass band, $\delta\omega_{pm}$ are given by equations (2.1.38) and (2.1.39).

(b) If p is even but m is odd or vice versa the result is the same as equations (2.1.36) and (2.1.37).

From equations (2.1.38) and (2.1.39) it can be seen easily that the pass band, $\delta\omega_{pm}$, is proportional to the perturbation $2\xi/d$, caused by periodic corrugations. But equations (2.1.36) and (2.1.37) show that this common rule is not always valid. In the case of the $\Delta x = 0$, described by equations (2.1.36) and (2.1.37), all Bragg gaps ($m = p$), for every mode, vanishes. The width of these pass bands is defined by equation (2.1.33). Thus, in the waveguide having the congruent periodic boundaries, a wave propagates without Bragg reflection.

In the case $\Delta x = \pi$, the Bragg gaps as well as the subminizone gaps have the maximum value given by equation (2.1.33).

Since the gaps in the spectrum correspond to the stop bands, the transmission coefficient of the waveguide into the x-direction drops to zero when a frequency of a wave coincides with the onset of the stop band.

2.1.5. Conclusion: Main Results Related the Wave Propagation in Planar Waveguide with Movable Plates

In this part of this thesis, it is shown that in the planar periodically corrugated waveguide, resonance interaction between transverse modes (standing-waves) occurs in a wide frequency range. Because of the interaction nature resonances (stop bands) occur. The Bragg reflection corresponds to the last stop band ($p = m$) in the subminizone spectrum of the mode as the stop band at the boundary of the first Brillouin zone. Number of stop bands (the same as the subminizones), including the Bragg gap, equals to the order number of the mode. For example, there are two subminizones in the spectrum of the second mode ($p = 2$).

The width of stop bands depends on the phase shift, Δx between parallel periodic boundaries and mode's evenness. It varies from zero to a maximum value while one plate shifting half period of corrugation with respect to another. In a case of the congruent boundaries, the Bragg stop bands don't open, and electromagnetic wave propagates in the periodic waveguide without Bragg reflections. When the frequency of the electromagnetic wave coincides with one of the gaps, only unidirectional propagation along grooves is allowed in the waveguide.

Thus when the plates are shifted the half period of corrugation, the two-dimensional guiding structure becomes the unidirectional guide and this situation creates the photonic waveguide. Via this method, controlling and adjusting of the width of the stop band and direction of the wave propagation can be applied into different applications in optoelectronics and microwave technology such as filters.

2.2. Statement of the Problem for Rectangular Periodically Corrugated Waveguides with Movable Plate

2.2.1 TEM Modes of a Rectangular Waveguide

For each possible index *m* we have a mode of propagation. Modes are labeled TE_{10}, TE_{20}, TE_{30}… The first index gives the periodicity (number of half sinusoidal oscillations) between the plates, along the x-direction. The second index is zero to indicate uniform solution along the y-direction. Note that the solution $m = 0$ (or mode TE_{00}) is not acceptable, because it would require a field configuration with uniform electric field tangent to the metal plates. This is an unphysical boundary condition, which is possible only for the case of trivial solution of zero field everywhere. Modes are labeled TM_{00} , TM_{10} , TM_{20} , TM_{30} , …

Note that the solution $m = 0$ (or mode TM_{00}) is acceptable, because the magnetic field can be uniform and tangent to the metal plates. The TM_{00} mode is like a portion of a uniform plane wave sliding between the plates of the waveguide. Both the electric and the magnetic field are transverse (normal to the guide axis) therefore this mode is usually known as Transverse Electro Magnetic mode (TEM).

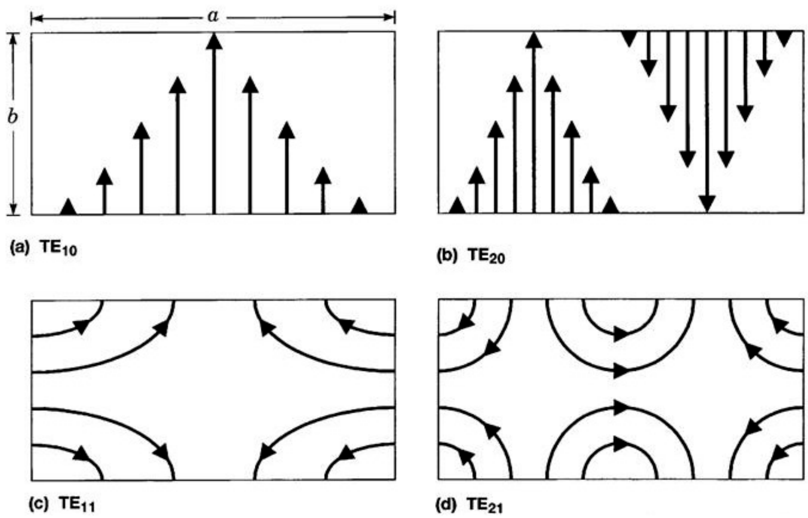
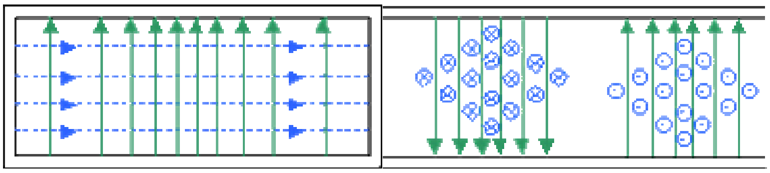
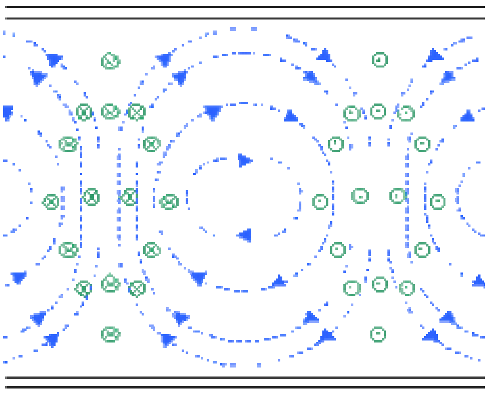


Fig. 2.4.TE modes in rectangular waveguide

TE (Transverse Electric) Mode The TE_{10} mode is the dominant mode of a rectangular waveguide with a>b, since it has the lowest attenuation of all modes. Either m or n can be zero, but not both.



End View (TE_{10}) Side View (TE_{10})

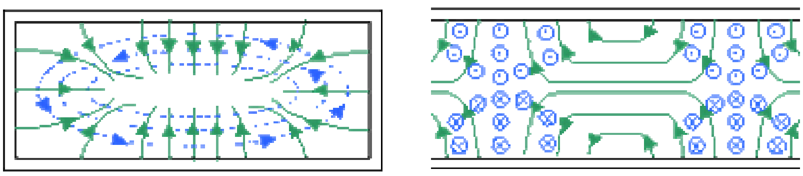


_____ Electric field lines
_ _ _ Magnetic field lines

Top View (TE_{10})

Fig. 2.5 Different view of TE_{10} mode

TM (Transverse Magnetic) Mode For TM modes, m=0 and n=0 are not possible, thus, TM_{11} is the lowest possible TM mode.



End View (TM_{11}) Side View (TM_{11})

_____ Electric field lines
_ _ _ Magnetic field lines

Fig. 2.6 Different view of TM_{11} mode

Because E is purely in the y direction for these TE modes, we can place two additional parallel conducting plates parallel to the x-z plane with any separation in the y direction so as to form a closed rectangular tube within which the waves still propagate. The instantaneous E field is suggested in Figure 2.7. Because E is everywhere perpendicular to the two new walls, and H is everywhere parallel, the new walls are consistent with all boundary conditions. We call this mode the TE_{20} rectangular waveguide mode because the TE fields extend two half-wavelengths (λ_x) in the longer dimension of the rectangle and zero half-wavelengths in the shortest dimension.

Rectangular waveguide modes for which $E_z = 0$ are designated TE waveguide modes because E is purely transverse to the direction of propagation, and modes with $H_z = 0$ are designated TM modes because H is purely transverse. In general we can have four plane waves bouncing inside closed rectangular waveguides, where $TE_{m,n}$ and $TM_{m,n}$ indicates the number of half-wavelengths in the standing wave patterns in the longer (m) and shorter (n) transverse dimensions.

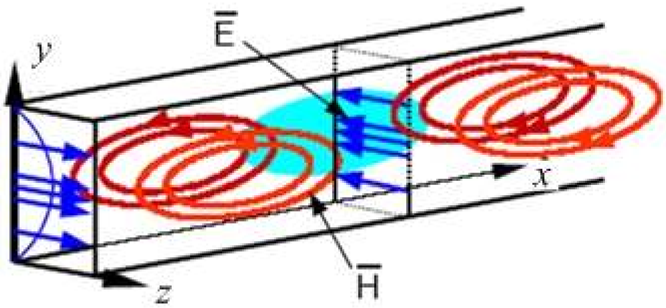


Fig. 2.7 . TE_{10} waveguide mode

Figure 2.7 portrays the same instantaneous electric and magnetic fields for the TE_{10} rectangular waveguide mode. It is clear that this wave is propagating in the +z direction, consistent with E xH. At the same time boundary conditions require surface charges to be present on the sides of the waveguide perpendicular to E. They are distributed sinusoidally across the waveguide surface, with zero charge on the other two walls where E equals zero.

2.2.2. Theoretical Results for Rectangular Waveguide with Movable Plate

In this part, wave phenomenon in planar periodically two dimensional corrugated waveguide is investigated. This special geometry is shown detailed in Figure 2.8.

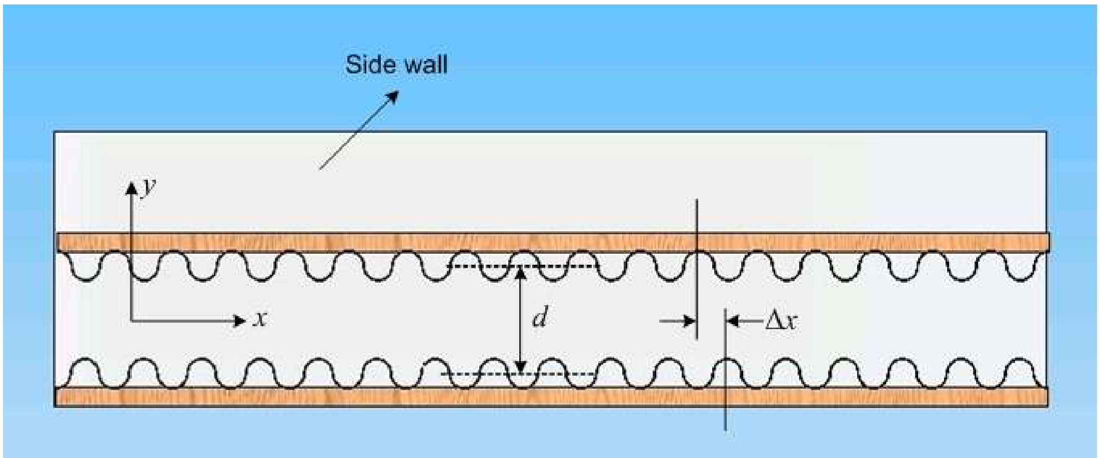


Fig. 2.8. Geometry of a rectangular periodically corrugated waveguide. The side boundaries located in along *z* direction with a width of *b*. The second one of the side walls is not represented here in order view inside of the structure clearly.

In this geometry, the special waveguide has two conductor plates as its upper and lower boundaries and dielectric medium occupies the space ($y_d(x) > y > y_{-d}(z)$) between these parallel plates. As it is seen from Figure 2.4, parallel plates have sinusoidal function as their profiles. Medium between the periodic boundaries is assumed to be linear, homogenous, isotropic and non-dispersive. Amplitude of upper and lower plate corrugations are ξ and expressions of upper and lower boundaries are $y_d(x) = d - \xi\cos(qx)$ and $y_{-d}(z) = \xi\cos(qz)$ respectively. In this geometry, $q = 2\pi/a$, a is the period of the upper and lower corrugation, d is average distance between upper and lower parallel plates. We assumed that the corrugations have a small amplitude i.e. $\xi/d << 1$, and $\xi q << 1$.

For the theoretical calculations of the rectangular waveguide, beside the above calculations for the planar periodically corrugated waveguide, it is necessary to set another boundary condition for the side walls. And second necessary equation for the solution, boundary conditions can be written as:

$$E(x, y_{-d}(z)) = E(x, y_d(x)) = 0 \tag{2.2.12}$$

$$E(z = 0) = E(z = b) = 0 \tag{2.2.13}$$

b is the width of the rectangular waveguide. This second boundary condition doesn't affect the rest of the calculations. The dispersion equation remains the same.

Due to the boundary periodicity, $E(x, y)$ can be represented in the form of a Fourier series (Floquet's theorem) as;

$$E(x, y) = \sum_n \left[a_n \cos(k_{y_n} y) + b_n \sin(k_{y_n} y) \right] e^{j(k_x + nq)x} \tag{2.2.14}$$

where k_x and k_y are the wave vectors in the directions of x and y respectively. Substitution of equation (2.2.14) into equation (2.2.11) give us a very useful equation, which includes the relation between ω and k.

$$\varepsilon \frac{\omega^2}{c^2} - (k_x + nq)^2 - k_{y_n}^2 = 0 \tag{2.2.15}$$

This relation can used to find the dispersion relation $\omega(k)$.

If we substitute $n = 0$ in above equation;

$$\omega^2 = \frac{c^2}{\varepsilon}({k_{x,p,m}}^2 + k_{0p}^2) \tag{2.2.16}$$

$$\omega_{pm} = \frac{c}{\sqrt{\varepsilon}} \left[k_{0p}^2 + \left(\frac{k_{0p}^2 - q^2 - k_{1m}^2}{2q} \right)^2 \right]^{1/2} \tag{2.1.17}$$

In vicinity of resonance, the more accurate solution of equation (2.1.15) shows that this resonant frequency splits into two values as ω_{pm}^{+} and ω_{pm}^{-}. And these two values are separated by the forbidden gap $\delta\omega_{pm}$. To reach more accurate solution of resonant frequencies and stop band, below procedures are done;

$$k_{\pm 1} = \frac{m\pi}{d}, \; m = 1, 2, 3, ... \tag{2.1.18}$$

$$k_0 = k_0^{(0)} + \delta k = \frac{p\pi}{d} + \delta k \tag{2.1.19}$$

From equations (2.1.14) and (2.1.19)

$$k_{\pm 1} = \sqrt{\frac{p^2\pi^2}{d^2} \pm 2k_x q - q^2} \tag{2.1.20}$$

and

$$k_{x,p,m}^{\pm} = \pm\frac{q}{2}(1 + X_{p,m}) \text{ where } X_{p,m} = \frac{(m^2 - p^2)\pi^2}{(dq)^2} \tag{2.1.21}$$

Then

$$\omega_{p,m}^{\pm} = \omega_{p,m} \pm \frac{c^2}{\varepsilon}\frac{p\pi^2}{d^3}\frac{m\xi}{\omega_{p,m}}\left[1 + (-1)^{p-m+1}\cos\Delta x\right]^{1/2} \tag{2.1.22}$$

$$\omega_{p,m}^{\pm} = \omega_{p,m}\left[1 \pm \sqrt{2}\,\frac{\xi}{d}\frac{\omega_{0p}\omega_{1m}}{\omega^2{}_{p,m}}\left[1 + (-1)^{p-m+1}\cos\Delta x\right]^{1/2}\right] \tag{2.1.23}$$

And the stop band appears as;

$$\delta\omega = \omega^{+}_{p,m} - \omega^{-}_{p,m} = 2\sqrt{2}\,\frac{\xi}{d}\,\frac{\omega_{0p}\omega_{1m}}{\omega_{p,m}}[1+(-1)^{p-m+1}\cos\Delta x]^{1/2} \qquad (2.1.24)$$

where

$$\omega_{0p} = \frac{ck_{0p}}{\sqrt{\varepsilon}},\ \omega_{1m} = \frac{ck_{1m}}{\sqrt{\varepsilon}} \qquad (2.1.25)$$

Finally we achieved such relation for dispersion. This equation will be the source equation of the experimental part of the thesis. And will be verified at next chapter of this thesis. The theoretical analysis showed the dependence of the width $\delta\omega_{pm}$ of the gap on the phase shift Δx between the periodic plates, and a thickness of the waveguide. Depending on the value of Δx the gap varies between zero and the maximum value.

3. EXPERIMENTAL INVESTIGATIONS OF MICROWAVE TRANSMISSION SPECTRUM

3.1. Setup Configuration for Measurements

In our experimental research we used this experimental set-up for measuring the microwave transmission. The notations are valid for all different types of waveguides that we designed and manufactured.

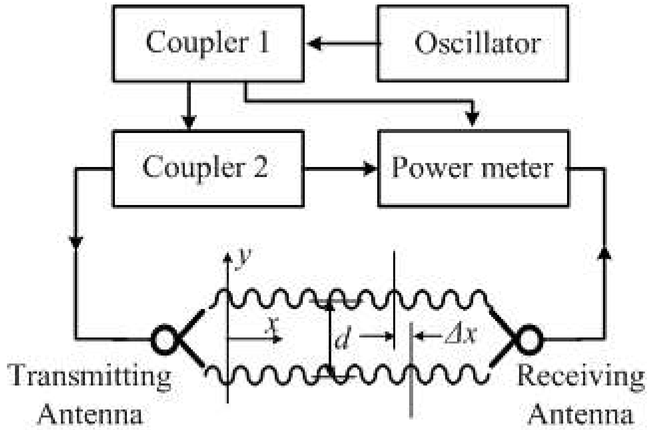


Fig. 3.1 Experimental setup for measuring the transmission properties of the periodically corrugated waveguide. The *z*-axis is perpendicular to the plane of the picture.

Features of devices that used during the experimental investigations:

Signal Source: FMI Model: 449X / 8.2GHz-12.5GHz

Rotary Attenuator: FMI Model: 16110

Frequency Meter: FMI Model: 16072

Directional Couplers: (Coupling Value:10dB) FMI Model: 16131-10

Adapter: AGILENT Model: X281A, FMI Model:16180

Power Sensors: AGILENT Model: 8481A

Waveguide Turning: FMI Model: 16450-90RH

Horn Antennas: FMI Model: 16240-15

Digital Power Meter: AGILENT Model: E4419B

Abbreviators that used in explanations of the graphs:

d : Average distance between parallel plates

a : Period of the corrugations

La-a : Distance between antennas

PS : Phase shift

Fcr : Critical frequency

F_{Br} : Bragg frequency

TP : Transmission Point

f : Frequency

P_i : Incident power

P_r : Received power

P_{rf} : Reflected power

3.2. Experimental Investigations

3.2.1 Transmission Spectrum for Planar Periodically Corrugated Waveguide with Movable Plates

The transmission properties of a planar waveguide, made of two metal plates having the identical sinusoidal profile $y(x) = \xi \cos(qx)$ were measured, where $q = 2\pi / a$, ξ and a are amplitude and period of the corrugation respectively, equal correspondingly to 0.415 cm and 3.15 cm in experimentation. The length of the structure was 82 cm which corresponded to 26 periods of the corrugation. The preliminary calibration measurement showed that a number of periods for optimal observation of the Bragg reflection range between 24 and 30. The width of the structure was chosen 70 cm, which was great enough to model it as the planar waveguide and decrease significantly the influence of the *z*-component of the wave vector into the field distribution.

The upper plate could slide with respect to the lower forming the phase shift Δx between them. The angle measure of the phase shift, θ, can be written as follows $\theta = (2\pi / a)\Delta x$. The relative position of the upper plate can be described, in this case, by the function $y_{up}(x) = \xi \cos(qx + \theta)$. The schematic of the standard microwave setup is shown in Fig.3.1 and the three-dimensional waveguide geometry is shown in Fig.3.2.

This waveguide was constructed from two corrugated zinc plates which are attached to wooden plates. The waveguide design, manufacturing and assembling performed in different workshops. The zinc plates attached to wooden plates which are necessary to be placed parallel to each other.

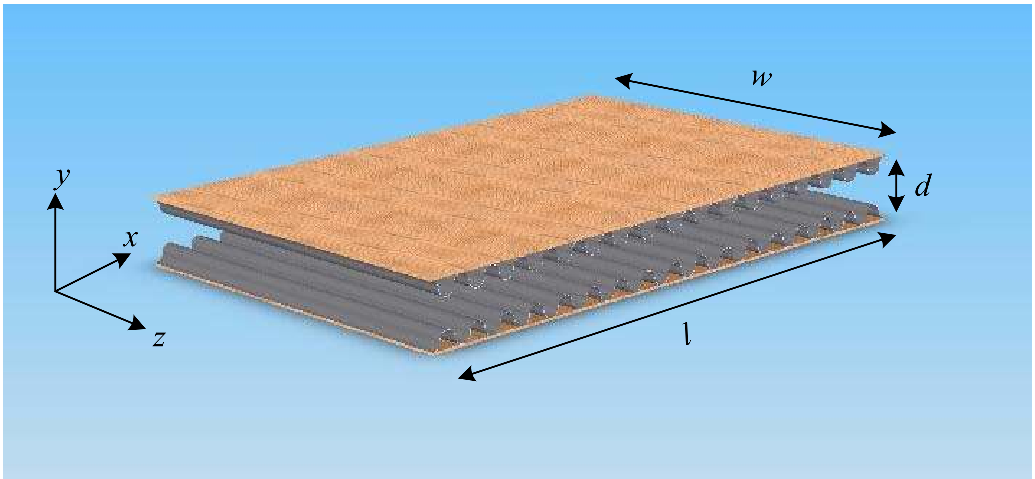


Fig. 3.2 The 3D view of planar corrugated waveguide. w (width of the waveguide) : 70 cm, l (length of the waveguide) : 84 cm, d (distance between the parallel plates): variable

3.2.1.1 Horizontal Polarization (TE Wave)

(1)Dependency of Transmitting Power vs Frequency

For these set of experiments microwave transmission is measured with a horn antenna. We have been investigated the propagation of the *TE* wave having the polarization vector parallel to grooves of the corrugation at the microwave range of frequency 8-12 GHz, was investigated. The average distance between parallel plates is d=8,6 cm.

The position of the Bragg gap, f_g , in the waveguide frequency spectrum and its width, δf_g, could be tuned by changing a waveguide thickness d and the phase shift between plates in accordance with formulas given in theoretical part of the thesis. At a certain waveguide thickness, f_g can coincide with one of the cutoff frequencies f_{0p}, where $f_{0p} = (c/2d)\,p$, c is speed of light, p is the mode index (p = 1, 2, 3..). In this geometric resonance case, the cutoff frequency splits into two values, separated by the gap δf_g. The wave propagation in vicinity of the cutoff frequency of the third mode was examined. For this mode, the resonant thickness, d_r, can be found from the formula

$$d_r = \frac{a}{2}\sqrt{p^2 - m^2} \quad . \tag{3.2.1}$$

Equation (3.2.1) can be rewritten as the relation between the transverse wave numbers $(\pi\, p/d)^2 = (\pi\, m/d)^2 + q^2$. For p = 3, the geometric resonance occurs at d_r = 4.5 cm and m = 1. The cutoff frequency splits into two values f_{31}^{+} and f_{31}^{-}.

$$f_{31}^{\pm} = \left[1 \pm \frac{\sqrt{2}}{3}\frac{\xi}{d_r}(1-\cos\theta)^{1/2}\right] f_{03} \tag{3.2.2}$$

where f_{03} is the cutoff frequency of the third mode for the smooth waveguide, for the given above thickness f_{03} = *10.02 GHz.* As it is seen from Eq. (3.2.2), a value of the gap, $\delta f_g = f_{31}^{+} - f_{31}^{-}$, depends on the phase shift θ between the plates. In a case of the symmetrical waveguide (symmetry with respect to the x-axis), $\Delta x = a/2$ i.e. $\theta = \pi$, Eq. (3.2.2) gives f_{31}^{+} = 10.63 GHz and f_{31}^{-} = 9.40 GHz, with a gap δf_{31} = 1.23 GHz. If $\Delta x = 0$ ($\theta = 0$, asymmetric waveguide), the gap vanishes. Fig. 3.3 shows the measured transmission properties of the waveguide for these two cases.

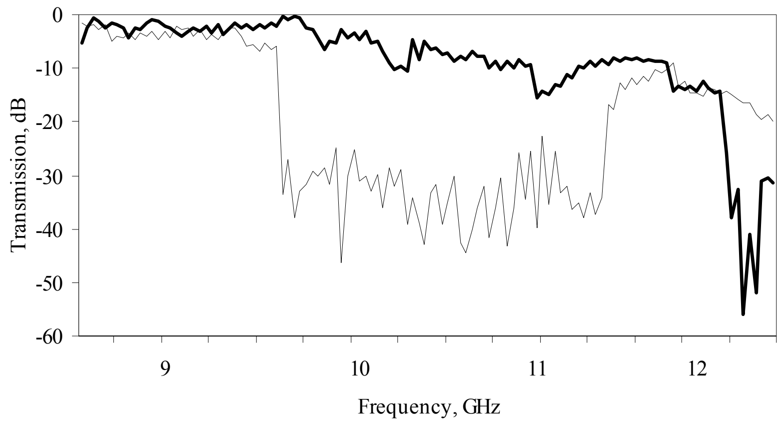


Fig. 3.3. Measured transmission characteristics for the periodically corrugated waveguide in two cases: the thin solid line for the symmetric waveguide, *Δx=a/2*; and the thick solid line for the asymmetric waveguide, *Δx* =0.

The symmetric waveguide, $\Delta x = a/2$, yielded the 1.24 GHz (thin line) band gap, close to the theoretical value of 1.23 GHz . This band gap vanished upon a shift of the upper plate by $\Delta x = a/2$ (thick line), and the wave propagated without Bragg reflection in the asymmetric waveguide. Only non-Bragg reflection is seen at f = 12 GHz.

(2) Dependency of Transmitting Power vs Phase Shift Between Parallel Plates

The transmission at a constant frequency of 8,806 GHz is shown in the Figure3.4 below. We observe the transmission at a constant frequency while shifting the upper plate with respect to the lower one step by step. The transmission plotted as a function of the phase shift Δx between the plates. Transmission is plotted as normalized power of 100.

The graph shows that the transmission varies from the minimum to maximum value upon a shift of one periodic plate with respect to another on the half period of the corrugation, *a*/2. For this measurement, the initial position of the plates was chosen at $\Delta x = a/2$ and then one plate was gradually moved back and forth on one period of the corrugation.

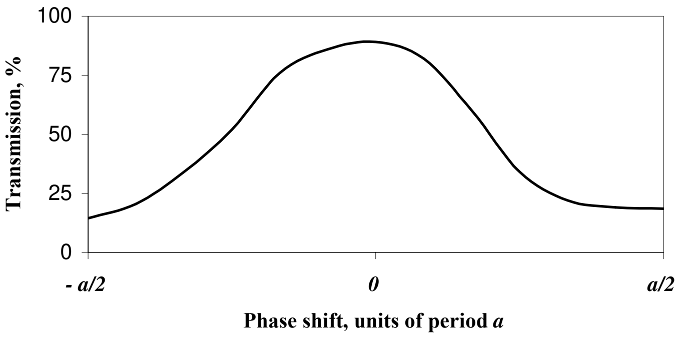


Fig. 3.4 The measured transmission through the corrugated waveguide at a fixed frequency of 8,806 GHz is plotted as a function of the phase shift Δx between the plates.

At constant frequency of 8,806 GHZ transmission property can be seen in the graph. The transmitted power changes from zero to a maximum value upon shifting the upper plate for half period of corrugation.

These experimental results are in a good agreement with formula (3.2.2), which describes the controllable band gap in the spectrum for the periodically corrugated waveguide.

3.2.1.2 Vertical Polarization (TM Wave)

(1) Dependency of Transmitting Power vs Frequency

For these set of experiments microwave transmission is measured with horn antennas placed at transmitting and receiving sides. We have been investigated the propagation of the *TM* wave having the polarization vector vertical to grooves of the corrugation at the microwave range of frequency 8-12 GHz, was investigated. For this experiment, the average distance between parallel plates d = 5,20cm.

(a) Phase Shift $\Delta x = a/2$

For the symmetric position of the corrugations, the transmission characteristic with respect to frequency for a *TM* wave is shown in the Figure 3.5 below. For the symmetric position of the parallel plates, there is a stop band occurred in the transmission spectrum of the waveguide. The theoretical calculations above that done for the *TE* Wave are valid for the *TM* Wave also. At symmetric position, the upper plate shifted half wavelength of the corrugation with respect to the lower plate.

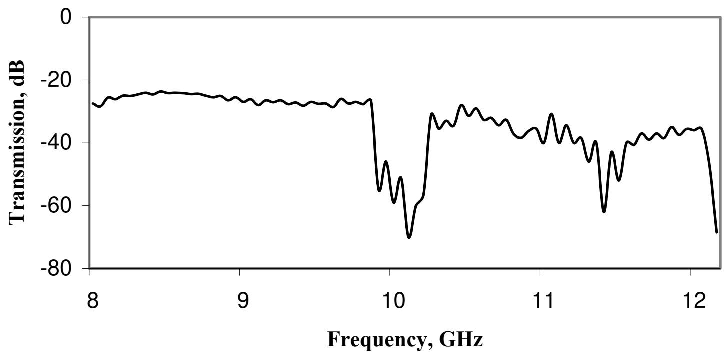


Fig. 3.5 Measured transmission characteristics of TM wave for the periodically corrugated waveguide at the symmetric position of the plates (upper plate shifted half wavelength of the corrugation with respect to lower plate), $\Delta x=a/2$, d=5,20 cm.

The width of the Bragg gap depends on the relative position of two periodic plates. It varies from zero to a maximum value upon shifting of one periodic plate with respect to another on the half period of the corrugation. When a frequency of the electromagnetic wave coincides with one of the gaps, the wave can not propagate through the waveguide.

(b) Phase Shift Δx = 0

For the asymmetric position of the corrugations Δx=0, the transmission characteristic with respect to frequency for a *TM* wave is shown in the Figure 3.6 below. For the asymmetric position of the parallel plates, the stop band vanishes in the transmission spectrum of the waveguide. This happens only after a phase shift of the upper plate by half wavelength of the corrugation with respect to the lower plate.

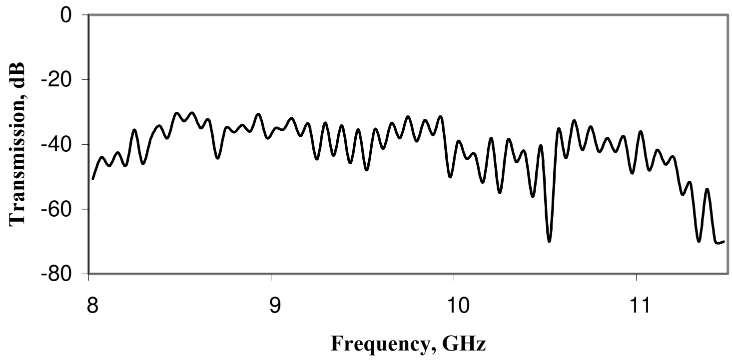


Fig. 3.6 Measured transmission characteristics of *TM* wave for the periodically corrugated waveguide at the asymmetric position of the plates, Δx=0, d=5,20 cm..

In this graph, it is seen that the Bragg gap vanished upon shifting the upper plate half period ($\Delta x = a/2$) of the corrugation with respect to lower one, and the wave propagated without Bragg reflection in the asymmetric waveguide.

These experimental results are in a good agreement with formula (3.2.2), which describes the controllable band gap in the spectrum for the periodically corrugated waveguide.

3.2.1.3 Planar Waveguide with Two-Dimensional Periodicity (Crossed Corrugations) Transmission Spectrum

The three-dimensional waveguide geometry is shown in Fig.3.7. This waveguide was constructed from two corrugated zinc plates which are attached to wooden plates. The waveguide design, manufacturing and assembling performed in different workshops. The zinc plates attached to wooden plates which are necessary to be placed parallel to each other.

The two of four corners have been cut in order to achieve such a position of the waveguide that the wave can be propagate on the plane of (x, -z) by a 45 degree angle to the x coordinate, through the direction B. We will denote this propagation as oblique incidence. We denote the transmission through x direction as normal incidence, while the electromagnetic wave propagates through the direction A.

The transmission properties of a planar waveguide with two-dimensional periodicity (crossed corrugations), made of two metal plates having the identical sinusoidal profile $y(x) = \xi \cos(qx)$ were measured, where $q = 2\pi / a$, ξ and a are amplitude and period of the corrugation respectively, equal correspondingly to 0.415 cm and 3.15 cm in experimentation.

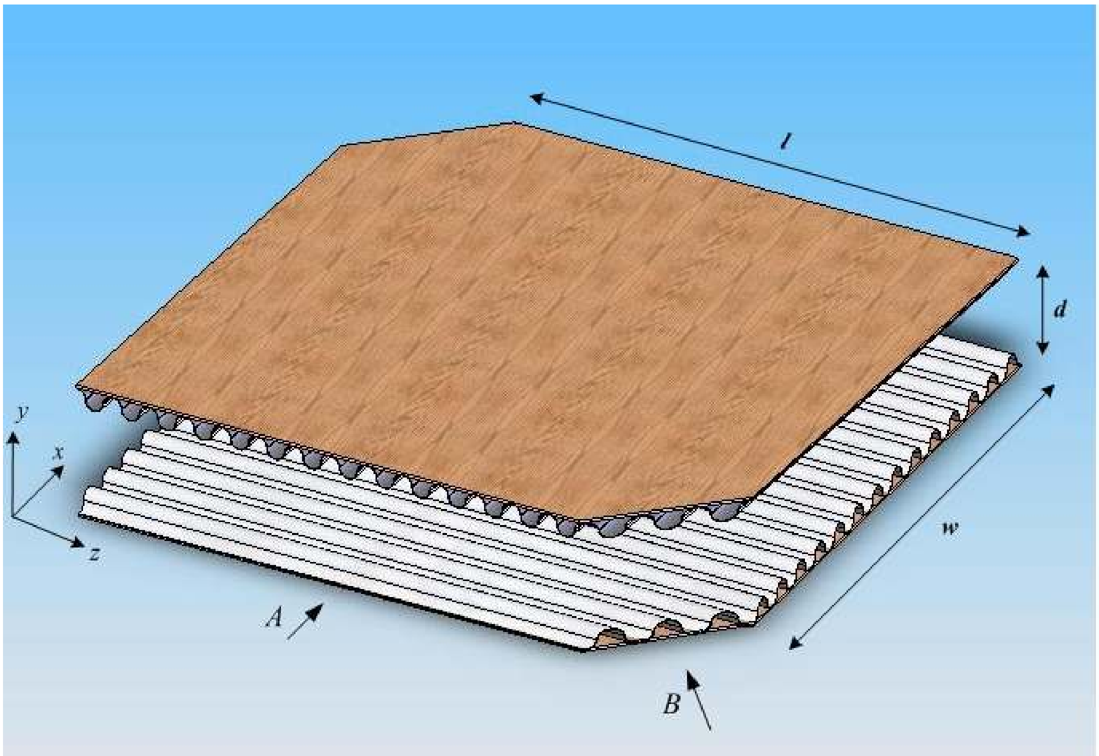


Fig. 3.7 The 3D view of planar waveguide with two-dimensional periodicity Transmission Spectrum. w (width of the waveguide) : 82 cm, l (length of the waveguide) : 82 cm, d (distance between the parallel plates): variable

The length of the structure was 82 cm which corresponded to 26 periods of the corrugation. As stated before, the preliminary calibration measurement showed that a number of periods for optimal observation of the Bragg reflection range between 24 and 30. The width of the structure was chosen 82 cm, which is necessary to assemble the crossed corrugation of upper and lower zinc plates and decrease significantly the influence of the *z*-component of the wave vector into the field distribution.

(1) Dependency of Transmitting Power vs Frequency

For these set of experiments microwave transmission is measured with horn antennas placed at transmitting and receiving sides. We will denote the propagation on the plane of (x, $-z$) by a 45 degree angle to the x coordinate, through the direction B as oblique incidence. The transmissions through the x coordinate through the direction A as normal incidence. We have been investigated the propagation of the *TM* wave having the polarization vector vertical to grooves of the corrugation at the microwave range of frequency 8-12 GHz, was investigated. For this experiment, the average distance between parallel plates is 2,80 cm

(a) Normal Incidence (Wave Propagation through *A* Direction) of the Waveguide

Transmission characteristics of the planar waveguide with two-dimensional periodicity (crossed corrugations) have investigated in this set of experiments. The chosen d (distance between parallel plates) is 2,80 cm. between the grooves of upper and lower plates. The transmitting and receiving antennas placed facing one another in order that the electromagnetic wave propagates through the position A.

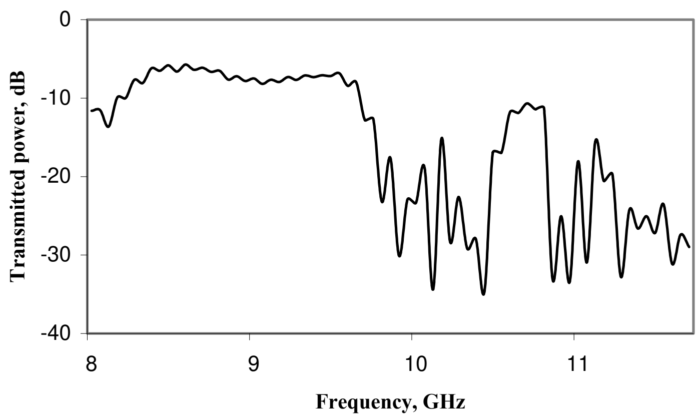


Fig. 3.8 Measured transmission characteristics for the planar waveguide with two-dimensional periodicity, in normal incidence of the waveguide. Wave propagates along A direction. d=2,80 cm.

Measured transmission characteristics shown in Figure 3.8. The stop band can be seen in that figure between 9,70 and 10,5 GHz. This proves the theoretical results can be applied to this type of the periodic waveguide.

(*b*) Oblique Incidence (Wave Propagation through *B* Direction) of the Waveguide

Transmission characteristics of the planar waveguide with two-dimensional periodicity (Crossed Corrugations) have investigated in this set of experiments. The chosen *d* (average distance between parallel plates) is 2,80 cm. The transmitting and receiving antennas placed facing one another in order that the electromagnetic wave propagates on the plane of (x, $-z$) by a 45 degree angle to the x coordinate, through the direction *B*.

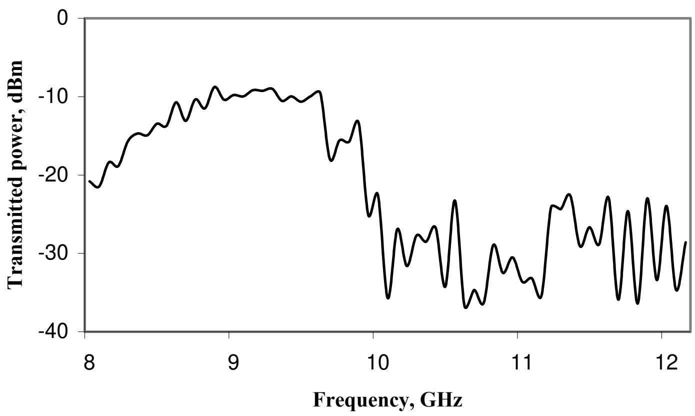


Fig. 3.9 Measured transmission characteristics for the planar waveguide with two-dimensional periodicity, in oblique incidence of the waveguide. Wave propagates along *B* direction. d=2,80 cm.

In Fig. 3.9 the measured transmission characteristics for the planar waveguide with two-dimensional periodicity, in oblique incidence of the waveguide is shown. It is seen that in these set of experiments, whether oblique or normal incidence, the stop band is visible in the transmission spectrum of waveguide.

3.2.1.4 Evaluation of the Results

The stop band is clearly seen when the plates are parallel position. The position of the Bragg gap, f_g , in the waveguide frequency spectrum and its width, δf_g, could be tuned by changing the distance between the parallel plates of the waveguide ***d*.** The experimental research proves that the theory of microwave transmission for periodically corrugated waveguide is valid for *TE* and *TM* waves.

The stop band is clearly seen when the phase shift is equal to *a/2*, and when the upper plate is shifted to half wavelength of the corrugation, phase shift=0, the gap vanishes. At constant frequency, when the upper plate is shifted by half wave length of corrugation, the transmission varies from minimum to a maximum value. This is a key feature of the research. This feature has many application areas in physics and technology. These experimental results are in good agreement with the theoretical results that described above sections.

The position of the Bragg gap, f_g , in the waveguide frequency spectrum and its width, δf_g, could be tuned by distance between the parallel plates of the waveguide *d* and the phase shift between plates. The experimental research proves that the theory of microwave transmission for periodically corrugated waveguide is valid for *TE* and *TM* waves.

3.2.2 Transmission Spectrum for Rectangular Corrugated Waveguide with Movable Plate.

The structure had designed and manufactured for these set of experiments. The structure is made of wooden and zinc parts. As for the corrugations, thickness of 0,30 mm corrugated zinc plate used. The corrugated plate has 60 cm length and 6 cm width. And the wooden parts, that the corrugated plates attached, have also 60 cm length and 6 cm width. The side walls are also made of smooth zinc plates. For the set of experiments it is necessary that the upper plate must be movable along *x* and *y* directions. As for this situation, the upper plate is movable along *x* direction in order to achieve phase shift between lower and upper plates. The upper plate is also movable along y direction, in order to adjust the distance between lower and upper plates.

The transmission properties of a rectangular waveguide, made of two metal plates having the identical sinusoidal profile $y(x) = \xi \cos(qx)$ were measured, where $q = 2\pi / a$, ξ and a are amplitude and period of the corrugation respectively, equal correspondingly to 0.415 cm and 3.15 cm in experimentation. The length of the structure was 60 cm, which corresponded to 19 periods of the corrugation. The width of the structure was 6 cm. The upper plate could slide with respect to the lower forming the phase shift Δx between them. The angle measure of the phase shift, θ, can be written as follows $\theta = (2\pi / a)\Delta x$. The relative position of the upper plate can be described, in this case, by the function $y_{up}(x) = \xi \cos(qx + \theta)$.

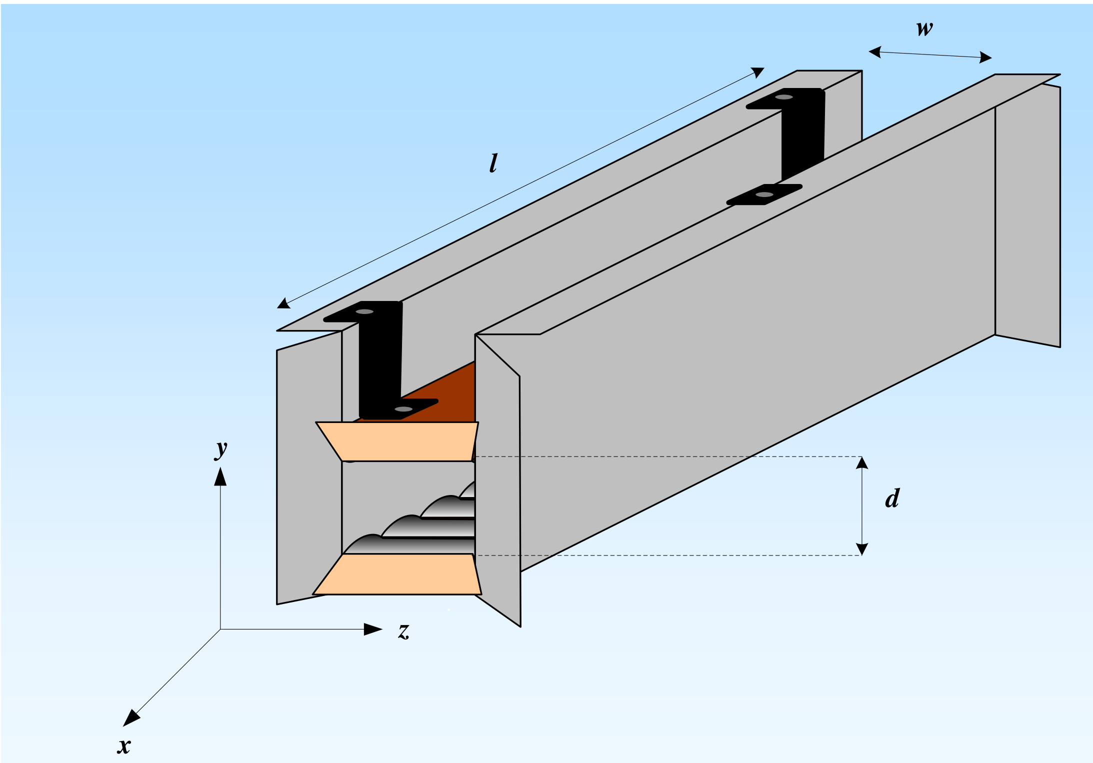


Fig. 3.10 The 3D view of Rectangular Corrugated Waveguide with Movable Plates. w (width of the waveguide) : 6 cm, l (length of the waveguide) : 50 cm, d (average distance between the parallel plates): variable

3.2.2.1 Horizontal Polarization (TE Wave)

(1) Dependency of Transmitting Power vs Frequency

(a) Phase Shift $\Delta x = a/2$

Measured transmission characteristics for the rectangular corrugated waveguide with movable plates for the symmetric position of the plates, $\Delta x = a/2$, is given in the Fig.3.11. In the Cartesian coordinate system, shown in Fig.3.1, the periodic plates are parallel to the *zx*-plane. The propagation of the TE_{10} wave has the polarization vector $\boldsymbol{E}$ parallel to the grooves of the corrugation (the *z*-axis).

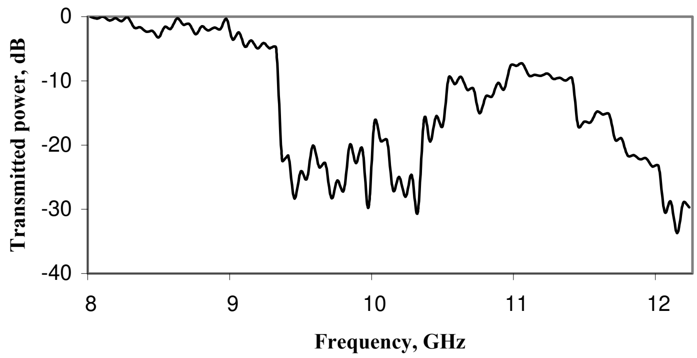


Fig. 3.11 Measured transmission characteristics for the rectangular corrugated waveguide with movable plates for the symmetric position of the plates, $\Delta x = a/2$; d=5,20cm.

Distance of transmitting antenna to waveguide = 4,7cm, distance of receiving antenna to waveguide =4,5cm, average distance between parallel plates = 5,20cm. The Bragg gap is observed at the frequencies between 9,3 GHz and 10,4 GHz.

(b) Phase Shift $\Delta x = 0$

Transmission characteristics that measured between 8-12 GHz, for the rectangular corrugated waveguide with movable plates for the asymmetric position of the plates, Δx=0, is given in Figure 3.12. It is clearly seen that the Bragg gap disappeared.

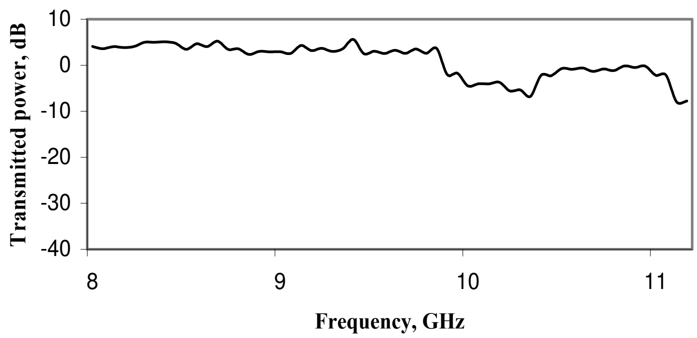


Fig. 3.12 Measured transmission characteristics for the rectangular corrugated waveguide with movable plates for the asymmetric position of the plates, Δx=0; d=5,20cm.

For these set of experiments, distance of transmitting antenna to waveguide = 4,7cm, distance of receiving antenna to waveguide =4,6cm and the average distance between parallel plates = 5,20cm.

(2) Dependency of Transmitting Power vs Phase Shift between Parallel Plates

The dependence of the transmission on the phase shift is plotted in Fig.3.13 for the selected band gap frequency of 9,58 GHz. It is seen that when the upper plate moves along x direction, with respect to the lower one, there is an evident power change occurs. The change occurs both in transmission and reflection patterns. The most interesting part of this experiment is that the evident change occurs by shifting only $a/2$.

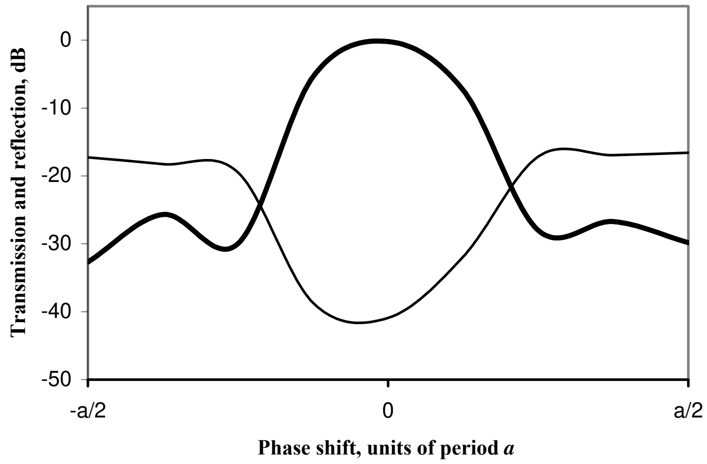


Fig. 3.13 The measured transmission (thick line) and reflection (thin line) through the corrugated waveguide at a fixed frequency of 9.58 GHz is plotted as a function of the phase shift Δx between the plates.

At constant frequency of 9,58 GHz, transmission property can be seen in the graph. The transmitted power varies from zero to a maximum value upon shifting the upper plate for half period of corrugation. For this measurement, the initial position of the plates was chosen at $\Delta x = a/2$ and then one plate was gradually moved back and forth on one period of the corrugation. The graph shows that the transmission varies from the minimum to maximum value upon a shift of one periodic plate with respect to another on the half period of the corrugation, *a*/2.

3.2.2.2 Evaluations of the Results

The experimental investigation is in good agreement with formula that describes change of the width of the stop band as a function of the phase shift Δx, and consequently the transmission through the waveguide. So this phenomenon can be applied to different tunable microwave devices.

In conclusion, the transmission properties of a planar periodically corrugated waveguide have been investigated experimentally. The 0.98 GHz band gap in vicinity of the cutoff frequency of the 3rd mode has been observed. Upon a shift of one of the plates with respect to another on a half period of corrugation, the gap vanished. In latter case, that of the congruent boundaries, an electromagnetic wave was propagated in the periodic waveguide without Bragg reflection indicating on gapless folding of dispersions in the spectrum for the periodic waveguide

In solid-state terminology, this spectrum transformation corresponds to the metal –insulator transition in the quantum wire, when the Fermi energy matches the gap. The wave properties of a periodic structure depend on a ratio between the wavelength and characteristic dimensions of the structure, therefore, the observed microwave properties are useful for modeling of electron phenomena in periodic quantum structures. The principal condition of observation of the properties caused by periodicity in solids is $l >> a$, where l is the electron mean free path, and a is a period of the lateral modulation. It is rigid enough condition that can be met usually at the helium temperature. The advantage of microwaves in such modeling is the very large "mean free path"of the electromagnetic wave, almost matching the electron mean free path in superconductors. Therefore, the mentioned condition is always met.

From this point of view, the laterally modulated quantum wire can be modeled by the periodically corrugated waveguide. Consequently the microwave experiment allows to model the electron quantum phenomena in micro- and nanostructures and to observe the effect of periodicity in the structures at the most favorable conditions.

5. CONCLUSION

Electromagnetic wave propagation in different type of periodically corrugated waveguides has been theoretically and experimentally investigated. We proved that the theoretical results are in good agreement with experimental results in all type of corrugated waveguides.

The propagation of microwaves through different types of hollow metallic waveguides has been investigated. Shape of walls that can stop transmission of electromagnetic radiation through the hollow metallic waveguide without closing its cross-section have been found. For this purpose, three pairs of planar corrugated waveguides and two pairs of rectangular corrugated waveguides with different length and one pair of crossed corrugated waveguide had manufactured. In order to achieve these results approximately two-hundred experiments had performed. And each experimental measurement needs approximately two hours of process.

It was shown that microwave transmission depends on the relative position of two periodically corrugated plates. The transmission varies from zero to a maximum value upon shifting one periodic plate with respect to another on the half period of the corrugation. This is the key feature of the tunability. This feature can be applied in designing tunable filters and switches. The results confirm the theoretical prediction of the geometry-driven spectrum transformation from the band structure spectrum to a gapless one upon such a shift of one of the plates.

We analyzed the propagation in periodically loaded waveguide structures and showed the existence of pass-bands and stop-bands, which are characteristic for periodic structures. It has been proved that, all results can be applied to any type of periodic structures and the theoretical and experimental results for horizontal polarization are also valid for vertical polarization of antennas.

The wave properties of a periodic structure depend on a ratio between the wavelength and characteristic dimensions of the structure, therefore, the observed microwave properties are useful for modeling of electron phenomena in periodic quantum structures. The principal condition of observation of the properties, caused by periodicity in solids, is $l >> a$, where l is the electron mean free path, and a is a period of the lateral modulation. It is rigid enough condition that can be met usually at the helium temperature. The advantage of microwaves in such modeling is the very large “mean free path” of the electromagnetic wave, almost matching the electron mean free path in superconductors. So the mentioned condition is always met. Another advantage is that the waveguide, unlike solid, allows investigating the dispersion of a separate mode. From this point of view, the waveguide can be considered as the empty of electrons crystal. Consequently the microwave experiment allows to model the electron quantum phenomena in micro-and nanostructures and to observe the effect of periodicity in the structures at the most favorable conditions.

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AUTOBIOGRAHY

I was born on 5th of July, 1981 in Adana. I continued my secondary and high school education in Adana Ticaret Odası Anadolu Lisesi with one year of English preparation course between years 1992-1999. After high school I attend to Electrical and Electronics Department of University of Çukurova in 2000. I graduated from the university in 2005. And I continued Master of Science program at Electrical and Electronics Engineering Department of University of Çukurova between years 2005-2006. Research areas of mine include periodic structures especially subject of "Rectangular Periodically Corrugated Waveguide with Movable Plates" with Prof. Dr. Victor Pogrebnyak.