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RESONANCE PHENOMENA IN A WAVEGUIDE-DIELECTRIC STRUCTURE

The physical processes occurring in the waveguide-dielectric structure that has the form of a section of rectangular cut-off waveguide with dielectric insertion filling completely the cross section of the waveguide are considered. There are travelling modes in the insertion.

The electromagnetic fields in the classic waveguide-dielectric resonator without devices for its excitation and with coupling elements are calculated. The expressions for the reflection and transmission coefficients of the structure under consideration are presented. The calculating results of the distribution of the modulus of the electric field along the longitudinal axis of the cut-off waveguide at the natural frequency and frequencies near to that are obtained. It is shown that the frequency deviation from the natural value greatly reduces the electric field inside the resonance volume. The positions of poles and zeros of the reflection coefficient are investigated with a fractional-rational approximation. The obtained results are useful for measuring the properties of dielectric materials using waveguide methods.

Keywords: waveguide-dielectric structure, resonance, fractional-rational approximation.

Рассматриваются физические процессы, имеющие место в волноводно-диэлектрической структуре в виде отрезка прямоугольного запредельного волновода с диэлектрической вставкой, полностью заполняющей поперечное сечение волновода. Во вставке существуют распространяющиеся волноводные моды.

Анализируется поведение электромагнитного поля в классическом волноводно-диэлектрическом резонаторе без учета устройств для его возбуждения, а также при использовании систем связи. Приводятся выражения для расчета коэффициентов отражения и прохождения исследуемой структуры. Приводятся результаты расчета распределения модуля напряженности электрического поля вдоль продольной оси запредельного волновода на резонансной частоте и на частотах, близких к ней. Демонстрируется, что отклонение частоты электромагнитного поля от резонансного значения приводит к значительному снижению напряженности электрического поля внутри резонансного объёма. С помощью дробно-рациональной аппроксимации исследуется расположение полюсов и нулей функции коэффициента отражения. Полученные результаты являются полезными для проведения измерений свойств диэлектрических материалов волноводными методами.

Ключевые слова: волноводно-диэлектрическая структура, резонанс, дробно-рациональная аппроксимация.

Розглядаються фізичні процеси, які відбуваються в хвилевідно-діелектричній структурі у виді відрізку закритичного прямокутного хвилеводу з діелектричною вставкою, яка повністю заповнює поперечний переріз хвилеводу. У вставці існують хвилеводні моди, що поширюються.

Аналізується поведінка електромагнітного поля у класичному хвилевідно-діелектричному резонаторі без врахування пристроїв для його збудження, а також при використанні систем зв'язку. Наводяться вирази для розрахунку коефіцієнтів відбиття та проходження досліджуваної структури. Наводяться результати розрахунку розподілу модуля напруженості електричного поля вздовж повздовжньої осі закритичного хвилеводу на резонансній частоті та на частотах, близьких до такої. Демонструється, що відхилення частоти електромагнітного поля від резонансного значення викликає значне зниження напруженості електричного поля всередині резонансного об'єму. За допомогою дробово-раціональної апроксимації досліджується розташування полюсів та нулів функції коефіцієнту відбиття. Отримані результати є корисними для проведення вимірів властивостей діелектричних матеріалів хвилеводними методами.

Ключові слова: діелектрично-хвилеводна структура, резонанс, дробово-раціональна апроксимація.

Introduction

In the present time, modern technologies and productions require the use of dielectric materials. It is necessary to obtain information about the properties of the dielectric material, such as its dielectric permittivity and its loss tangent. Various microwave methods are used to solve this problem. Among them an important place is occupied by devices using waveguide-dielectric structures.

Many papers [1-4] are devoted to the consideration of the devices on the basis of waveguide segments with dielectric inserts. According to the authors, the first attempt to produce a classification of the waveguide-dielectric systems was presented in [5]; there the basic physical ideas were realized. However, according our opinion, such analysis has only the proposition nature and, for example, the physical processes in a rectangular waveguide with a dielectric insert have not been completely analyzed.

The purpose of this paper is considering the resonance phenomena in such systems. The rectangular waveguide with a dielectric box completely filling the cross-section of the waveguide has been taken as an example. The choice of the proposed structure is determined by the fact that it has an analytic solution of the electromagnetic problem; the results of the analysis can be generalized for more complicated cases.

Main part

Let us consider the classic pattern of the waveguide-dielectric resonator excluding devices for its excitation. It is presented in the Fig. 1.

(a) **(b)**

Fig.1. A waveguide-dielectric resonator model without its excitation device (a) and the variation of the cut-off waveguide excitation with dielectric filling inserts(b)

As known, the electromagnetic field components E_y, H_x and H_z of the main type of the mode H_{10} in a rectangular waveguide are not zeroes. If the origin of the longitudinal coordinate is situated in the middle of the dielectric insert, there are two cases in view of the axis of symmetry of the system under consideration: the first one is the situation when the magnetic wall is in the middle of the dielectric parallelepiped; and the second one – when the electric wall is in the middle of the dielectric parallelepiped. In the first case the electric field in the dielectric insert can be described by the expression

$$E_y = A\cos(\gamma z) \tag{1}$$

and the other case is

$$E_y = A\sin(\gamma z)\,. \tag{2}$$

The electric field outside the dielectric in both cases is described by the expression

$$E_y^0 = A_0 \exp(-\gamma_0 z)\ , \tag{3}$$

where A, A_0 are amplitude coefficients, $\gamma = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 \varepsilon - \left(\frac{\pi}{a}\right)^2}$, $\gamma_0 = \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{\pi}{a}\right)^2}$ are propagation constants in a waveguide filled with a dielectric and in an empty one respectively, a is the size of the wide side of the waveguide, λ is the length of the electromagnetic wave in the waveguide, ε is dielectric permittivity.

The required tangential component H_x of the magnetic field is: $H_x = -A\frac{\gamma}{j\varpi\mu}\sin(\gamma \cdot z)$ in the first case and $H_x = A\frac{\gamma}{j\varpi\mu}\cos(\gamma \cdot z)$ in the second. Outside the dielectric it is $H_x^0 = -A_0\frac{\gamma_0}{j\varpi\mu}\exp(-\gamma_0 z)$, where ϖ − cycle frequency, μ is the permeability of the medium. The boundary conditions for the tangential components E_y, H_x of the electromagnetic field can be satisfied only in the plane $z = \frac{L}{2}$ due to the symmetry of the system with the origin of z-coordinate in the center of dielectric slab, where L is the thickness of the dielectric insert. In the first case, the boundary conditions for E_y and H_x are $A\,cos\left(\gamma\frac{L}{2}\right) = A_0\,exp\left(-\gamma_0\frac{L}{2}\right)$ and $A\gamma\,sin\left(\gamma\frac{L}{2}\right) = A_0\gamma_0\,exp\left(-\gamma_0\frac{L}{2}\right)$, respectively.

The condition for determining the natural frequencies is obtained via dividing the first expression by the second one

$$ctg(\gamma\frac{L}{2}) = \frac{\gamma}{\gamma_0}. \tag{4}$$

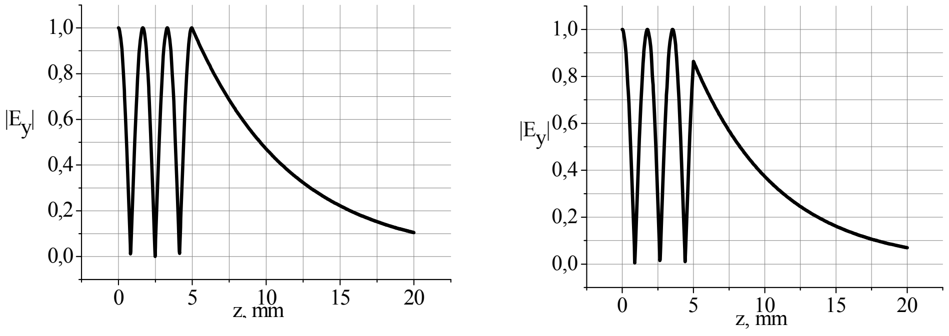
The similar expression for the second case is

$$tg(\gamma\frac{L}{2}) = -\frac{\gamma}{\gamma_0}. \tag{5}$$

Such approach of similar ideology was used by the authors of papers [6] with certain complications in satisfying the boundary conditions at the ends of waveguide systems with a dielectric filling.

A necessary condition for the initiation of resonance properties, as it is known, is the abrupt intensity changing of the electromagnetic field in a resonant volume with respective frequency changing. It should be noted that there are two radically different physical natures of the manifestation of resonant properties for the considered model. In the first case the resonance system is formed by a segment of a standard waveguide with traveling mode in the corresponding frequency band. In the other case, the waveguide segment is cut-off one without any traveling mode but a traveling mode exists in the dielectric insert. For the first case the equations for determining the natural frequencies have complex solutions, so natural frequencies also must be complex. This corresponds to the loss due to the electromagnetic energy radiation. It is a radical difference from the other case, in which the presence of the cut-off waveguide eliminates the radiation loss.

In our paper we consider the case with the cut-off waveguide as the simplest version for calculations. The size of the wide side of the waveguide a = 12 mm provides a dominant mode in the 3-cm wave-range. Let us suppose that hypothetical dielectric material has the dielectric permittivity ε = 80 and thickness L = 10 mm, under conditions of absence dielectric losses ($\mathrm{tg}\delta = 0$). In the case of the solution with magnetic wall (4), the chosen geometrical and electrical parameters of the system give the value of natural frequency f = 10242 MHz. At this frequency the distribution of the electric field strength modulus along the longitudinal axis from the point of symmetry in the dielectric insert and in the part of space outside is shown in Fig. 2a. The influence of the frequency changes on the distribution of the electric field strength modulus is illustrated in Fig. 2b.



(a) **(b)**

Fig. 2. The electric field strength modulus along the longitudinal axis of the cut-off waveguide at resonance frequency f_R = 10242 MHz (a) and near it f = 9600 MHz (b) for parameters of dielectric insert: a = 12 mm, $L/2$ = 5 mm, ε = 80

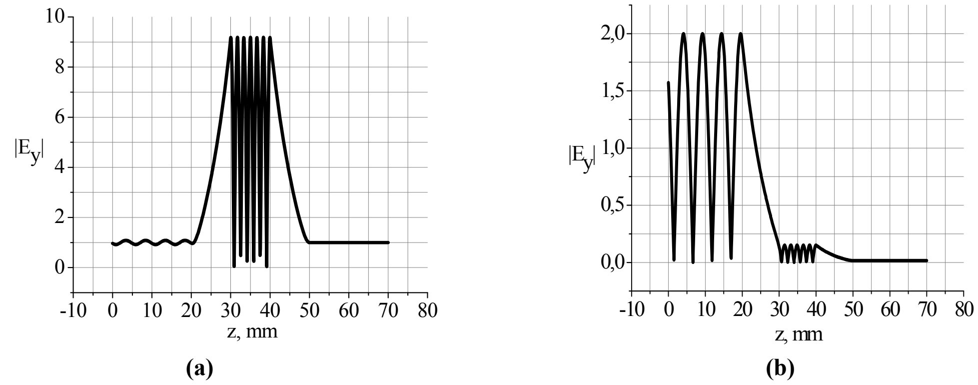
The view of the field with $L/2$ = 5 mm is considered in this figure due to the system symmetry. As we can see from Fig. 2b, the frequency deviation of the electromagnetic field from the natural one leads to a slight decrease of the strength only in the plane of the dielectric permittivity jump. Hence, it is clear that such simplified model of the waveguide-dielectric resonator can not give a full description of the physical processes occurring in this structure.

Obviously, for more complete description of processes in such structure it is necessary to take into account the devices for excitation of the cut-off waveguide inserts connected to the dielectric sample. There are several versions of the devices for excitation of cut-off waveguides. For example, in [8] a sharp change of sizes of the cross section in H-plane is used; according to [9] multilayer dielectric filling of the cut-off waveguide can be used; using coaxial transition is presented in [6]. For the succeeding analysis we shall use the model that has been shown in Fig. 1b, as the simplest one for the electromagnetic calculation.

Using the boundary conditions for the E_y, H_x components of the electromagnetic field in the planes of dielectric permittivity jumps, we can obtain the expressions for the complex transmission $T = \frac{1+R}{1+r_1}\cdot\frac{e^{-\gamma_0 d}+r_1 e^{\gamma_0 d}}{1+r_2}\cdot\frac{e^{-\gamma L}+r_2 e^{\gamma L}}{1+r_3}\left(e^{-\gamma_0 d}+r_3 e^{\gamma_0 d}\right)\cdot e^{\gamma_1 d}$ and reflection $R = \frac{q-1}{q+1}$ coefficients for this structure, where $q = \frac{\gamma_1}{\gamma_0}\cdot\frac{1+r_1}{1-r_1}$, $r_1 = \frac{q-1}{q+1}e^{-2\gamma_0 d}$, $q_1 = \frac{\gamma_0}{\gamma}\cdot\frac{1+r_2}{1-r_2}$, $r_2 = \frac{q_2-1}{q_2+1}\cdot e^{-2\gamma L}$, $q_2 = \frac{\gamma}{\gamma_0}\cdot\frac{1+r_3}{1-r_3}$, $r_3 = \frac{q_3-1}{q_3+1}\cdot e^{-2\gamma_0 d}$, $q_3 = \frac{\gamma_0}{\gamma_1}$, and d is the length of the unfilled part of the waveguide, L is the length of the central dielectric insert. The longitudinal distribution of the electric field strength along the cut-off waveguide with three dielectric parallelepipeds has been calculated.

Fig. 3 shows the corresponding results. Geometrical and electrical parameters are the size of the wide side of the waveguide a = 12 mm, the length of the external dielectric parallelepipeds L_h = 20 mm and permittivity ε_1 =10, the length of the unfilled part of the waveguide d = 10 mm, the length of the central parallelepiped L= 10 mm and its dielectric permittivity ε = 80. The estimated resonance frequency is 10250 MHz for this configuration. The distribution for the resonance frequency is presented in Fig. 3a.

Fig. 3b shows a longitudinal distribution of the electric field strength for the same system, but the frequency of the electromagnetic field is 10000 MHz. The comparison of Fig. 3a and Fig. 3b shows that, as it follows from the theory of resonance phenomena, the deviation of the electromagnetic field frequency from the resonance value induces sharp reduction of the electric field strength inside the resonant volume in contrast to the results which have been obtained for the simple model.



(a) **(b)**

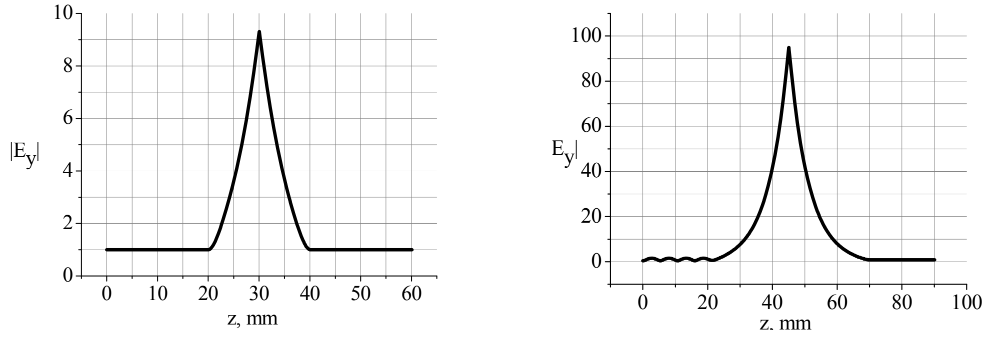
Fig. 3. The electric field strength modulus along the longitudinal axis of the cut-off waveguide structure that has been shown in Fig. 1b at resonance frequency f_R = 10250 MHz (a) and near it f = 10000 MHz (b) with structure parameters: a = 12 mm, d = 10 mm, L = 10 mm, ε_1 = 10, ε = 80

Some difference in frequencies for the first and the second models can be explained by the fact of coupling device effect on the resonance phenomena in the second model. The following example will show this effect. Let us consider the case where the dielectric insertion is a film of the thickness of 0.1 mm and all the other parameters remain unchanged. The results of calculation of the longitudinal distribution of the electric field strength for the length of the unfilled part of the waveguide d = 10 mm has been shown in Fig. 4a and corresponding ones for d = 25 mm are presented in Fig. 4b. Length d =10 mm corresponds to the resonant frequency of 9943 MHz and d = 25 mm corresponds to 9752 MHz; it can be explained by changing the influence of the coupling constant of the exciting element on the resonance volume. For d = 25 mm the electric field strength increases by about an order of magnitude and oscillations of the electric field strength appear in the area of the first dielectric parallelepiped.

Moreover, the range between the minimum and maximum values of electric field strength has increased in tens times in comparison with the case of L = 10 mm. In the case of d =10 mm, L=10 mm the frequency deviation of the electromagnetic field from the resonance value leads to a sharp decrease of the electric field strength (Fig. 5).

For a comparison, the natural frequency for the first model (with the same geometrical sizes and electrical parameters of the central dielectric parallelepiped) determined from the equation (4) is 9750 MHz. It practically coincides with the frequency (9752 MHz) for the second model with d = 25 mm. Thus, their natural frequencies determined from the simplest equation (4) coincide with the natural frequencies of the second model with sequential decreasing of coupling coefficients.

The values of the poles and zeros have been obtained by fractional-rational approximation [10] of the structure reflection coefficients as functions of frequency. It is well known that the positions of the poles coincide with resonance frequencies. The fact of convergence of the values of the poles and the calculated resonance frequencies confirms that the considered dielectric waveguide structure really manifests resonance phenomena.



(a) **(b)**

Fig. 4. The distribution of the electric field strength modulus along the longitudinal axis of the cut-off waveguide structure (a = 12 mm, d = 10 mm, L = 0.1 mm, ε_1 = 10, ε = 80) has been shown in Fig. 1b with various d : d = 10 mm, f_R = 9943 MHz (a), d = 25 mm, f_R = 9752 MHz (b)

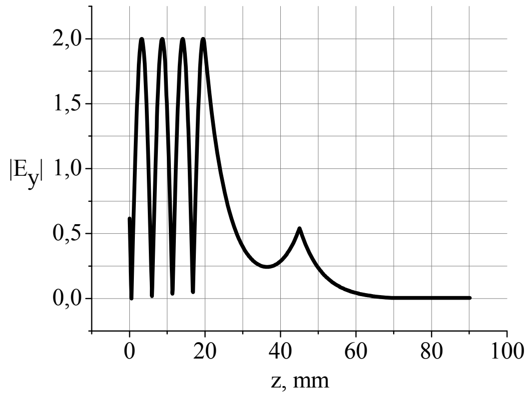


Fig. 5. The electric field strength modulus along the longitudinal axis of the cut-off waveguide structure (a = 12 mm, d = 25 mm, L = 0,1 mm, ε_1 = 10, ε = 80) at frequency f = 9600 MHz

Conclusions

As was shown, not every dielectric waveguide system, which has a resonance-like frequency dependence of the reflection or transmission coefficients, is actually a resonator system. The results have shown that the waveguide-dielectric system with a coupling element, which was presented by the completely filled dielectric parts of the cut-off waveguide, was the resonator. It was evidenced by the sharp reduction of the electric field strength modulus at the deviation of frequency from the natural one. The obtained results are useful for express measurements of dielectric material parameters with waveguide methods.

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