Quasioptical Selective Elements for MM-Wavelength Range Based on Interference Grid Structures

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Abstract – The results of theoretical investigations of quasioptical interference structures based on crossed grid-polarizers are presented. It is shown that such structures have the possibility of smooth varying their spectral and polarization characteristics: width and form of transmission or reflection bands, polarization ellipse parameters, that is a principal advantage in comparison with alternative structures. A test variant of the 3-grid structure is being in preparation for diagnostic application in hot experiments on generation of powerful 75 GHz radiation at ELMI-device as a tunable band-pass filter.

1. Introduction

One-dimensional and two-dimensional grids comprised by thin conductors (wires) with a grid pitch less than wavelength serve as important elements of millimeter and submillimeter devices operating on quasioptical principles. In particular, such grids were successfully used in constitutive interference structures or filters as semitransparent reflectors [1, 2].

The simplest two-grid structure is a Fabry-Perot filter (Fig. 1) which provides a radiation transmission band with the relative bandwidth

$$\frac{\Delta\lambda}{\lambda} = \frac{1-R}{m\pi\sqrt{R}}. \qquad (1)$$

Here m is an interference order and R is a grid reflectance which depends on the grid parameters g, a, t and the wavelength λ [2]. For $m \sim 1$ the important case of the narrow band regime is realized when $g \ll \lambda$. The incident polarization has no matter for 2-D grids with square cells, but should be of the E-type for 1-D grids (for the H-wave the 1-D grid is transparent). The polarization insensitivity of 2-D grids has defined their main application in multigrid interference structures, whereas 1-D grids are used more often as single free standing polarizers or beam dividers.

It is important to stress that selective characteristics of interference structures based on 2-D grids or identically oriented 1-D grids for the fixed interference order are defined completely by the grid parameters, and can be changed only by substitution of grids for the ones with the other values of g, a, t. In this paper we present the main results of theoretical investigations of the novel type of interference grid structures with smoothly variable selective characteristics which do not have a disadvantage of grid substitution. These structures are comprised by 1-D grid-polarizers with variable crossed orientation of conductors in adjacent grids. Due to the strong polarization sensitivity of the separate grids the spectral and polarization characteristics of the constitutive structures appear to be strongly dependent on the relative crossing angles of 1-D grids.

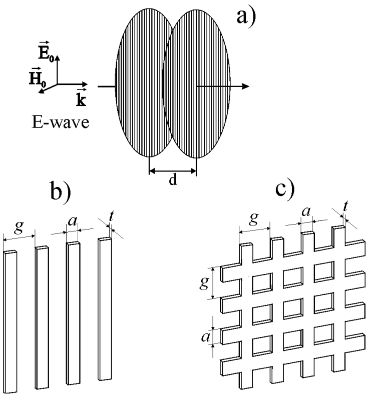

Fig. 1. Principal scheme of microwave Fabry-Perot filter (a) and possible variants of its reflectors: 1-D (b) and 2-D (c) conductive grids

2. Theoretical Description of Interference Structures Based on Crossed 1-D Grid-Polarizers

a) Initial ideas

As a preliminary illustration of the crossed polarizers idea, consider a "Fabry-Perot"-like structure with constitutive reflectors comprised by pairs of ideal crossed grid-polarizers (Fig. 2a). The term "ideal polarizer" means that a grid completely reflects the E-wave and totally transmits the H-wave. Formally it corresponds to the condition $g/\lambda \to 0$ and the infinite grid conductivity.

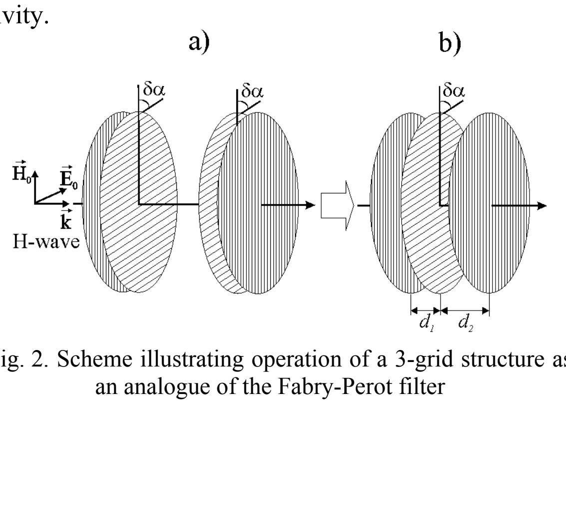

Fig. 2. Scheme illustrating operation of a 3-grid structure as an analogue of the Fabry-Perot filter

The distinctive feature of the ideal case is choice of incident wave polarization, which is opposite to the case of conventional Fabry-Perot structure: the wave falling on a constitutive reflector should be of the H-type with respect to its first grid, since the E-wave is reflected completely and the second grid has no influence on the constitutive reflector transmittance.

It is clear further that the smoothly varied orientation angle $\delta\alpha$ provides smooth changing the effective reflectance R_{eff} of the constitutive reflector. For example, $R_{\text{eff}} = 1$ for the case of $\delta\alpha = \pi/2$ and we should expect zero width transmission bands accordingly to the formula (1). Finally, let us notice that the identical orientation of two middle grids allow us to simplify the 4-grid structure to the 3-grid one (Fig 2b). This structure has three performance parameters which determine its selective properties: the grid distances d_1, d_2 and the orientation angle $\delta\alpha$.

b) Quasioptical approach

For the rigorous description of the crossed grid-polarizers structures and verifying the initial ideas we offered the quasioptical approach presented in [3]. This approach is based on matrix generalization of the conventional scalar interference optics theory to the case of 1-D grids as anisotropic layers. Thus, any grid of the constitutive structure is characterized by its transmission $\Im_n$ and reflection $\Re_n$ Jones matrices:

$$\Im_n = \begin{pmatrix} \tau_n^E \cos^2\alpha_n + \tau_n^H \sin^2\alpha_n & (\tau_n^E - \tau_n^H)\cos\alpha_n \sin\alpha_n \\ (\tau_n^E - \tau_n^H)\cos\alpha_n \sin\alpha_n & \tau_n^E \sin^2\alpha_n + \tau_n^H \cos^2\alpha_n \end{pmatrix}.$$

Here n is a consecutive number of the grid, τ_n^E and τ_n^H are its amplitude transmittances for E- and H-waves, α_n is an orientation angle of the grid conductors, the matrix $\Re_n$ is derived from $\Im_n$ by substitution $\tau_n^E \to \rho_n^E$, $\tau_n^H \to \rho_n^H$, where ρ is an amplitude reflectance. The following calculation of the selective properties of the constitutive structure containing the arbitrary number of grids is based on matrix formulas which have the similar form as scalar optics formulas. For instance, in important case of the 3-grid structure shown on Fig. 2b its transmission matrix obtained by the recurrent formulas method [3] is calculated as

$$\mathbf{T}_3^{\rightarrow} = \Im_3 \left[\mathbf{I} - \mathbf{R}_2^{\leftarrow} \Re_3 e^{2i\gamma_2} \right]^{-1} \mathbf{T}_2^{\rightarrow} e^{i\gamma_2}, \qquad (2)$$

where

$$\mathbf{R}_2^{\leftarrow} = \Re_2 + \Im_2 \Re_1 \left[\mathbf{I} - \Re_2 \Re_1 e^{2i\gamma_1} \right]^{-1} \Im_2 e^{2i\gamma_1},$$

$$\mathbf{T}_2^{\rightarrow} = \Im_2 \left[\mathbf{I} - \Re_1 \Re_2 e^{2i\gamma_1} \right]^{-1} \Im_1 e^{i\gamma_1}, \gamma_1 = kd_1, \ \gamma_2 = kd_2.$$

c) Ideal polarizers limit

The extreme case of ideal grid-polarizers [4] corresponds to the conditions: $\tau_n^E \equiv 0$, $\rho_n^E \equiv -1$, $\tau_n^H \equiv 1$, $\rho_n^H \equiv 0$. In case of H-polarization ($\mathbf{E_0} = (E_0, 0)$) the calculation by means of (2) the energetic transmittance of the 3-grid structure with orientation angles $\alpha_1 = \alpha_3 = \pi/2$, $\alpha_2 = \alpha$ gives the following result:

$$T_3^H = \frac{4\sin^2\gamma_1 \sin^2\gamma_2}{\text{ctg}^4\alpha \ \sin^2(\gamma_1+\gamma_2) + 4\sin^2\gamma_1\sin^2\gamma_2}.$$

The spectral transmittance T_3^H reveals its strong dependence on the value of α (see Fig. 3).

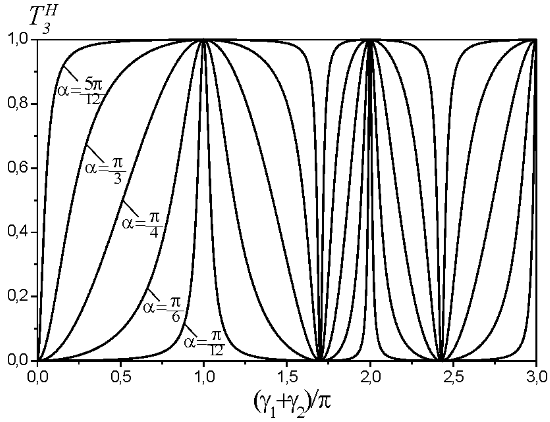

Fig. 3. The typical spectral transmittance of the 3-grid structure for various values of the medium grid orientation angle

α ($d_1/d_2 = 0.7$). H-polarization

There are two different regimes being of practical interest. As it was expected earlier for almost orthogonal relative orientation of the intermediate and edge grids ($\alpha \ll 1$, or $\delta\alpha \equiv (\pi/2 - \alpha) \cong \pi/2$) the 3-grid structure has narrow transmission bands. In this case the transmittance maxima bandwidth, which positions are defined as $\gamma_1 + \gamma_2 = m\pi$ ($m = 1, 2, 3,\ldots$), tends to zero quadratically with α:

$$\frac{\Delta\lambda}{\lambda_m^{\max}} \cong \frac{4\,\phi_m \alpha^2}{m\,\pi}, \qquad (3)$$

$$\phi_m = \begin{cases} \cos^2\Delta_m, & m\text{- odd} \\ \sin^2\Delta_m, & m\text{- even} \end{cases}, \quad \Delta_m = \frac{\pi m}{2}\frac{(d_1 - d_2)}{(d_1 + d_2)}.$$

Formal comparison of the formulas (3) and (1) allows to consider the 3-grid structure as an analogue of the Fabry-Perot structure with the effective reflectance $R_{\text{eff}} = 1 - 4\phi_m\alpha^2$. Notice that R_{eff} depends not only on the angle α, but the phase parameter ϕ_m as well.

The opposite narrow band regime is realized when the intermediate grid-polarizer is oriented almost identically as the edge ones: $\delta\alpha \ll 1$ or $\alpha \cong \pi/2$. In this case the structure reveals narrow band reflection for wavelengths derived from the conditions: $\gamma_j = n_j\pi$, $n_j \neq m$ ($n_j = 0, 1, 2, 3\ldots$; $j = 1, 2$). The reflection bandwidth is

$$\frac{\Delta\lambda}{\lambda_{n_j}^{\min}} \cong \frac{\delta\alpha^2}{n_j\pi}.$$

The more detailed analysis of ideal interference structures with other number of crossed grid-polarizers and orientational configurations is presented in Ref. [4]. Here it should be mentioned that in comparison with the 3-grid structure the structures containing the greater number of grid-polarizers have the possibility of varying both their transmission (reflection) bandwidths and band forms, and in particular allow to obtain bands with steeper edges. The Fig. 4 illustrates the spectral transmittance of the equidistant 3-grid and 5-grid structures ($\gamma = 2kd$, $k = 2\pi/\lambda$). The last one has the following configuration: $\alpha_1 = \alpha_3 = \alpha_5 = \pi/2$, $\alpha_2 = \alpha_4 = \alpha$.

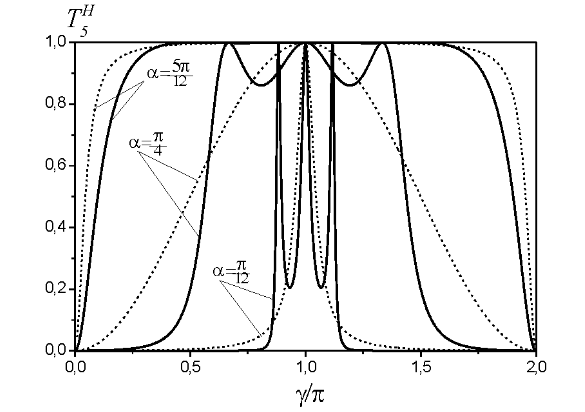

Fig. 4. The spectral transmittance of the 3-grid (dotted lines) and 5-grid (solid lines) structures for different orientation angles α. H-polarization

d) Effects of polarizers nonideality

Let's consider the case of a weak deviation of polarizing properties of the grids from the ideal polarizers limit. Our consideration will be restricted to the effects of the finite ratio of wavelength λ to the grid pitch g. The most compact analytical formulas can be obtained for the thin grid-polarizers which satisfy the condition $a \ll g$, where a is a grid conductor transverse size. In this case the amplitude transmittance and reflectance of grids can be expressed via the only parameter of nonideality A:

$$\tau_n^E \cong iA/(1+iA)\,,\ \rho_n^E = \tau_n^E - 1\,,\ \tau_n^H \cong 1\,,\ \rho_n^H \cong 0\,.$$

For $g \ll \lambda$ and $a \ll g$ the parameter $A \ll 1$ and negative. It depends on conductor geometry and for the most important practical cases might be written as

$A \cong 2g/\lambda \cdot \ln[\pi a/g]$ – the grid of cylindrical wires;

$A \cong 2g/\lambda \cdot \ln[\pi a/2g]$ – the grid of thin stripes ($t \ll a$).

The principal property of the nonideal case is the possibility of interference structure operation both on H- and E-polarized waves. It us clear from the fact that a conventional "nonideal" 1-D grid Fabry-Perot structure operates on E-polarization. The Fig. 5 presents the results of spectral transmittance calculation for the nonideal 3-grid structure for different types of incident polarization. The curves are obtained for the nonideality parameter $A = -0.1$ that corresponds to the 1-st interference order.

As seen from Fig. 5a, in case of H-polarization ($\mathbf{E_0} = (E_0, 0)$) the "nonideal" transmission maxima are shifted to the far wavelength region. The relative shift value with respect to the ideal maxima position appears to be equal to $\Delta\lambda_{shift}/\lambda^{max} \cong -A/m\pi$. In addition to the shift the two other negative effects of nonideality occur: bandwidth widening and decline of maximum transmittance when $\alpha \to 0$. These effects are described by formulas

$$\frac{\Delta\lambda}{\lambda_m^{max}} \cong \frac{4\,\phi_m \alpha^2 + A^2}{m\,\pi}\ ;\ T_{max}^H \cong \frac{4\,\phi_m \alpha^2}{4\,\phi_m \alpha^2 + A^2}\,. \quad (4)$$

The formulas (4) can be rewritten in the more conve-nient form which expresses the bandwidth via T_{max}^H:

$$\frac{\Delta\lambda}{\lambda_m^{max}} \cong \frac{1}{m\,\pi}\,\frac{A^2}{(1 - T_{max}^H)}\,. \quad (5)$$

For example, the condition $T_{max}^H > 0.5$ does not allow to obtain bandwidth less than $2A^2/m\pi$.

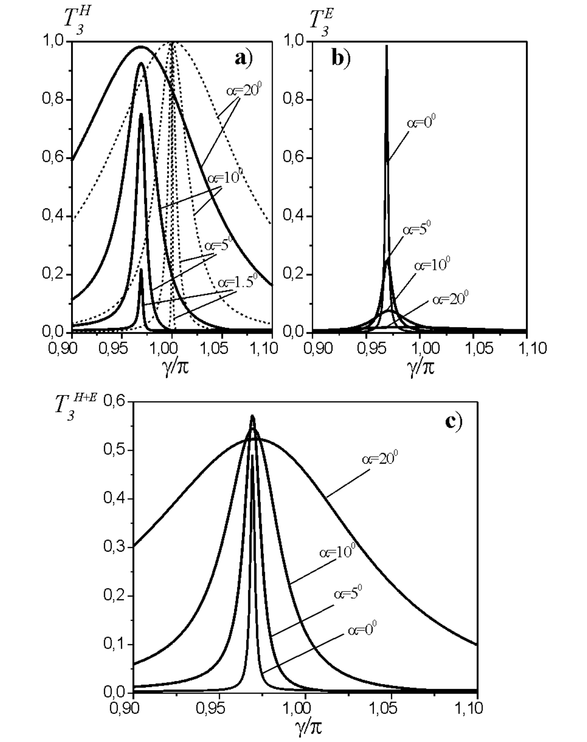

Fig. 5. Illustration of influence of polarizers nonideality on the spectral properties of the 3-grid structure ($d_2/d_1 = 0.7$): a) H-polarization (dotted curves correspond to the ideal case); b) E-polarization c) "hybrid" polarization

In case of E-polarization ($\mathbf{E_0} = (0, E_0)$), see Fig. 5b, the 3-grid structure also reveals the possibility of bandwidth retuning but, due to the maximum transmittance decline when α increases, such retuning is restricted to the rather short interval:

$$\frac{A^2}{m\pi} \le \frac{\Delta\lambda}{\lambda_m^{max}} \le \frac{1}{T_{max}^E}\frac{A^2}{m\pi}\,.$$

One of the methods for increasing the bandwidth retuning range at the high transmittance condition is to operate on "hybrid" polarization. The Fig. 5c corresponds to the polarization $\mathbf{E_0}= E_0\ (1/\sqrt{2}\ ,\ 1/\sqrt{2}\ )$, for which $T_{\max}^{E+H} > 0.5$ and minimal bandwidth is $A^2/m\pi$.

Among the positive effects of polarizers nonideality we could point out at the possibility of varying the polarization characteristics of transmitted (reflected) radiation. Fig. 6 demonstrates the behavior of the squared ratio ξ^2 of the small semi-axis to the big one for the polarization ellipse of the transmitted wave for the case of a 2-grid structure (the right figure corresponds to the spectral maximum of ξ^2). As seen, the narrow spectral bands of ellipticity exist and it is possible to adjust the fixed value of ξ^2 for desired wavelengths.

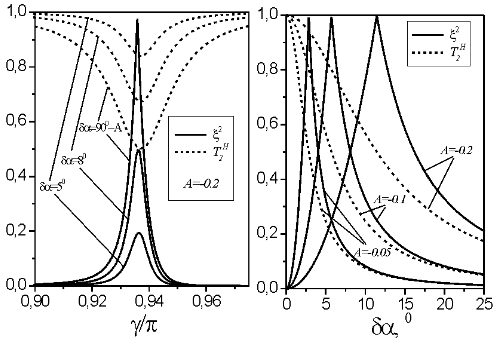

Fig. 6. Behavior of transmittance (dotted lines) and polarization ellipse characteristics (solid lines) of the 2-grid structure for different values of the crossing angle δα and nonideality parameter *A*. H-polarization

e) On the possibility of application for high-power microwave systems

The interference structures based on crossed grid-polarizers could be successfully applied as frequency and polarization selective elements of microwave systems and devices. However, it is necessary to notice that in case of a high level of incident power the problem of electrical breakdown inside a structure exists.

For instance, calculations show that for the worst case of "ideal" polarizers, which corresponds to the highest Q-factor case, the maximum electric field amplitude inside a 3-grid structure increases in $(\alpha\cdot|\phi_m|)^{-1}$ times in comparison with the incident H-wave amplitude. On the intermediate grid "surface" the total electric field appears to be directed orthogonally to grid wires and its amplification factor equals to simply α^{-1}. In practice such amplification of the internal field should be taken into account.

3. Experimental Activity

The present work is carried out in the framework of investigations on generation of powerful 4-mm radiation by a free electron maser operating with two-dimensional distributed feedback (ELMI-device, BINP, SB RAS) [5]. The work is aimed at the development of quasioptical diagnostics for the spectral analysis of generated radiation, which is used simultaneously with heterodyne diagnostics.

The quasioptical diagnostics used in the current experiments is built on conventional Fabry-Perot filters (Fig. 1). Such filters are based on 2-D grids and manufactured by chemical etching the thin (0.5–1 mm thickness) foil-clad textolite. The typical parameters of grids, which we use, are: $g = 0.8$–1.2 mm, $a = 0.3$–0.5 mm, $t = 0.018$–0.04 mm, the operating grid aperture size – Ø110 mm. In the last series of experiments the Fabry-Perot diagnostics has provided 0.8 GHz transmission band ($m = 2$), which could be scanned through the generated spectrum from 72 to 77 GHz. In the nearest future we plan to set in operation a new interference filter based on 3 crossed wire grid-polarizers. By now we have a semiautomatic device for winding high quality wire grid-polarizers with an optical control of winding accuracy. The device allows to wind simultaneously a couple of grids with an operating aperture size up to 200 mm and a grid pitch down to $g = 0.22$ mm. For the further application we have finished the winding of four polarizers on the base of gilded tungsten wire with diameter $a = 0.07$ mm. The grid pitch was chosen equal to $g = 0.22$ mm that provides the close to zero parameter of grid nonideality *A*. By now the grids are in stage of preparation to test measurements.

4. Conclusion

The results of performed theoretical investigations allow to conclude that interference structures based on crossed 1-D grid-polarizers have the evident advantage with conventional structures: the possibility of smooth varying their spectral and polarization characteristics. Such structures can find successful application as selective elements in millimeter and submillimeter systems of low and medium power. For high power systems special methods of incident power decrease should be undertaken for avoiding the internal breakdown problems.

Some theoretical problems of important practical significance are not discussed in the paper. These problems concern the questions of finite wire conductivity, inaccuracy of wire positions in grids, aperture diffraction. Along with experimental investigations, which are in the stage of development, these problems will be considered in future research.

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