Planar Bragg Resonators for Generators of mm-Wave Radiation[1]

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Electrodynamic properties of two-dimensional Bragg resonators of planar geometry realising two-dimensional (2D) distributed feedback are studied theoretically and experimentally. It has been shown that the 2D Bragg resonators possess high selectivity over both longitudinal and transverse mode indexes and can be used for provision of spatial coherence of radiation in powerful microwave generators driven by large size sheet electron beams. Dependence of the 2D Bragg resonators eigenmodes spectrum on the corrugation profile and side conditions is studied. Results of the theoretical analysis agree well with the data obtained in "cold" measurements in the vicinity of 60 and 75 GHz. Special planar device based on the Bragg gratings is developed for radiation output from generator.

1. Introduction

The development of a high-power free-electron maser (FEM) based on a relativistic electron beam of sheet geometry is under progress currently in collaboration between Budker Institute of Nuclear Physics (Novosibirsk, Russia), Institute of Applied Physics (Nizhny Novgorod, Russia) and Research Center Karlsruhe (Karlsruhe, Germany) [1-2]. The use of such a beam makes it possible to increase the total beam power and, correspondingly, the microwave power while still keeping the current and radiation density per unit transverse size constant. The use of two-dimensional (2D) distributed feedback has been proposed [3, 4] to provide spatial coherence and mode control in such strongly oversized system. The first operation of the novel feedback mechanism was demonstrated at the ELMI accelerator (BINP RAS) in the planar 75-GHz FEM based on a small-scale sheet electron beam (1 MeV/1.5 kA/5 μs) having a transverse cross-section of 0.3 cm×12 cm.

The 2D distributed feedback can be realised in 2D Bragg structures forming 2D Bragg resonators. It should be noted that presently the traditional one-dimensional (1D) Bragg resonators are widely used in the fast-wave high-power microwave oscillators including FEMs and cyclotron autoresonance masers (CARMs). The 1D Bragg resonators consist of waveguides sections with single-periodical corrugation of the walls and realize 1D distributed feedback with the coupling and mutual scattering of forward and backward (in the respect to the electron beam transitional motion) electromagnetic (e.m.) fluxes. However such resonators are able to provide mode selection only for the system with the transverse size of a few wavelengths. As a result, the output power produced in FEM experiments exploiting 1D Bragg resonators did not exceed few tens of. In contrast with traditional 1D Bragg structures novel 2D Bragg structures possess double-periodical corrugation in two-directions with an angle to each other. The feedback loop arising on such a type corrugation alongside with forward and backward e.m. fluxes includes as well the fluxes propagating in the transverse directions. These e.m. fluxes synchronise radiation from different parts of a large-size sheet electron beam.

The double-periodical shallow sinusoidal corrugation of the inner surfaces of metal plates, which forms a planar resonator, is the ideal realization of the 2D Bragg structure. However for the practical reasons some approximations of such a 2D corrugation can be used. In this paper different profiles including "ideal sinusoidal", "rectangular grooves", "chessboard pattern" corrugations, etc. are considered and compared for better realization of the 2D feedback mechanism. Obviously, any periodical profile can be expanded in Fourier series and above corrugations differ by amplitude of the parasitic 1D harmonics which cause direct coupling of counter propagating e.m. energy fluxes. The influence the 1D harmonics on the mode spectrum of 2-D Bragg resonators is studied in the present paper. Results of the theoretical analysis are compared with experimental data where the frequency dependence of the reflection coefficients on the 2D Bragg structures was tested.

2. 2D Bragg resonators

A planar 2D Bragg resonator consists of two metal plates (Fig.1a), either one or both are doubly corrugated in such a way that the translational vectors of the corrugations ($\vec{\bar{h}}_{\pm}$) are directed at an angle φ to

[1] The work was supported by RFBR (grants 04-02-17118 and 05-02-17036).

each other (Fig.1b). Operation of a 2D Bragg resonator is based on scattering of four perpendicular-propagating partial waves on this corrugation:

$$\vec{E} = \mathrm{Re}\left[\left(A_+ \vec{E}_{a+} \mathrm{e}^{-ih_{a+}z} + A_- \vec{E}_{a-} \mathrm{e}^{ih_{a-}z} + B_+ \vec{E}_{b+} \mathrm{e}^{-ih_{b+}x} + B_- \vec{E}_{b-} \mathrm{e}^{ih_{b-}x}\right) e^{i\omega t}\right]. \quad (1)$$

One of the partial waves (let assume A_+ as this wave) propagates along the electron beam and provides an interaction with the electrons. Two other partial waves $B_\pm$ propagate in transverse directions and should provide synchronisation of radiation from different parts of a wide sheet electron beam. The backward (with the respect to the electron beam) wave A_- forms the feedback cycle.

A 2-D Bragg structure may be produced in several different ways. Four possible versions of the structures are shown in Fig.2. An "ideal" 2-D sinusoidal corrugated structure (Fig.2a) provides effective coupling and mutual scattering of the four partial waves (1) if the wavenumbers $h_{a\pm}$ and $h_{b\pm}$ of the partial waves satisfy to the Bragg resonance condition (Fig.1b):

$$h_{a\pm} \approx \bar{h}_z \ , \ h_{b\pm} \approx \bar{h}_x \ . \quad (2)$$

However, such a surface is rather difficult to be manufactured and in the first experimental tests some approximation of sinusoidal profile has been used (Fig.2b, c, d).

The simplest 2D structure to manufacture seems to be a Bragg structure machined from rectangular grooves in two perpendicular *(φ=90°)* directions (Fig.2b).

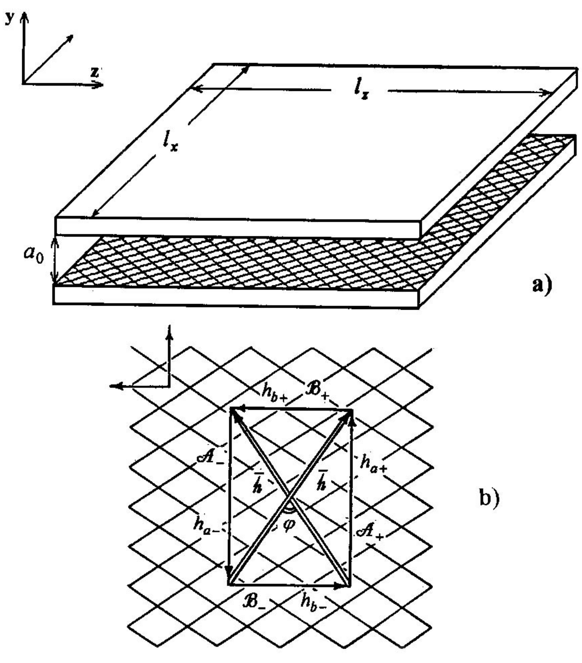

Fig. 1. Planar 2D Bragg resonator.

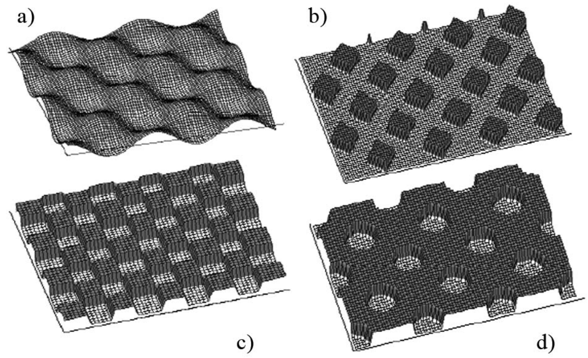

Fig. 2. 2D Bragg structures: "ideal" sine corrugation (a), rectangular grooves (b), "chessboard" pattern (c) and periodical holes (d)

In particular, the Bragg structures of such a type were used in the first experiments at the ELMI accelerator [1, 5]. The main disadvantage of this corrugation is that its Fourier expansion represents a combination of a 2D term and additional 1D terms providing two feedback circuits. Besides 2D scattering (i.e. scattering defined by the loop $A_+ \leftrightarrow B_\pm \leftrightarrow A_-$, see Fig.1b) of the four partial waves with the same wave numbers ($h_{a\pm} = h_{b\pm} = h$), which takes place under the Bragg resonance condition (2) there is a traditional 1D Bragg scattering (i.e. direct scattering $A_+ \leftrightarrow A_-$ and $B_+ \leftrightarrow B_-$) [6] when two opposite propagating partial waves satisfy the resonance condition:

$$h_{a+} + h_{a-} \approx 2\bar{h} \ , \ h_{b+} + h_{b-} \approx 2\bar{h} \ . \quad (3)$$

The additional 1D resonances (3), which appear on the "non-ideal" corrugation, lead to significant changes in the eigenmodes spectrum of a 2D Bragg structure [7, 8]. Also, due to the direct coupling under condition (3) of the counter propagating waves with different wavenumbers $h_{a\pm}$ (and different transverse structures over the *y*-axis) the additional frequency zones of the traditional 1D Bragg scattering occur on the 2D structures with profile different from ideal sinusoidal corrugation.

A much more satisfactory approximation for the sinusoidal corrugation is a so-called "chessboard pattern" corrugation (Fig.2c). It is important to note also that in the Fourier expansion of such pattern there are no the even harmonics, which provides parasitic 1D scattering. It should be noted however that when manufacturing real "chessboard pattern" corrugation some inaccuracies would take place especially at the corners of the corrugation. These would result in the appearance other harmonics in the Fourier expansion and, in particular, additional 1D harmonics with the amplitude ε depending on the manufacturing accuracy. As an alternative to the "chessboard structure" the "periodical holes" structure shown in Fig.2d can be considered. The main terms of the Fourier expansion for this structure have the same form, where the amplitude ε depends on the relation between the period of the structure and the diameter of the holes.

3. Eigenmodes of a 2-D planar Bragg resonator

In the frame of the geometrical optics mutual scattering of the four partial waves (1) may be described by the set of coupled-wave equations for the slow functions $A_{\pm}(x,z)$, $B_{\pm}(x,z)$ [3, 4]. The spectrum of the resonator eigenmodes may be found from the solution of these equations in the assumption of the electromagnetic energy fluxes from outside the resonator to be absent and also with proper boundary conditions for the partial waves.

Figure 3 shows transformation of the 2D Bragg resonator eigenmodes spectrum ($h_{a\pm} = h_{b\pm} = h$, Bragg frequency mismatch $\delta = h - \bar{h}$) with the grows of the 1D scattering admixture, caused by increasing 1D wave coupling coefficient (the wave coupling coefficients α_{2D} [4] and α_{1D} [6] depend on the corrugation type and depth). An analysis of coupled-wave equations shows that 2D Bragg resonator with different corrugation profile with quit arbitrary relation between α_{2D} and α_{1D} provide high selectivity over both the longitudinal (n) and the transverse (m) indices [8].

For the resonator with "ideal" sinusoidal 2D corrugation ($\alpha_{1D} = 0$) eigenmodes are located near the Bragg resonance $\delta \approx 0$ as well as near $\delta \approx \pm 2\alpha$. In this case the spectrum of eigenmodes is symmetrical over the Bragg resonance frequency $\bar{\omega} = \bar{h}c$ (i.e. $\delta = 0$) and the highest Q-factor is achieved at the precise Bragg frequency at the eigenmodes with indices $\{n = 0, m = 1\}$ or $\{n = 1, m = 0\}$. Admixture of direct scattering of the opposite propagating waves (i.e. $A_+ \leftrightarrow A_-$ and $B_+ \leftrightarrow B_-$) destroys symmetry of the eigenmodes spectrum. With the increase of the admixture of 1D scattering the spectrum is shifted to a low frequency region. As a result, for the "rectangular grooves" corrugation, which corresponds to the case $\alpha_{1D} = 1.2\alpha_{2D}$, the highest Q-factor is realised for the eigenmodes having one field variation along both coordinates $\{n = 1, m = 1\}$ and positioned near $\delta \approx \alpha_{1D}$ and $\delta \approx -2\alpha_{2D} - \alpha_{1D}$. Figure 3 gives also the frequency dependencies of the integral coefficients of reflection from 2D Bragg resonator assuming an incident wave with a plane phase profile entering at the resonator edge. This modelling is necessary for interpretation of data obtained in "cold" resonator testing. The reflection coefficient is also symmetrical over the Bragg frequency in the case of an "ideal" resonator and increase non-symmetry with the increase in admixture of 1D scattering.

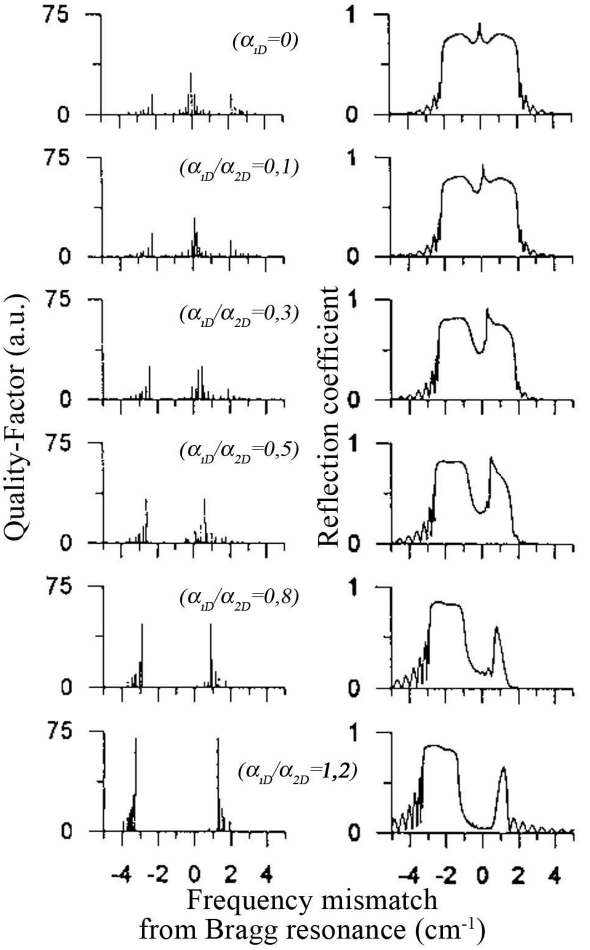

Fig. 3. 2D Bragg resonator eigenmodes and reflectivity at various 1D scattering admixture (simulation results).

4. Results of "cold" tests

Experimental study of the electrodynamic properties of 2D planar Bragg resonators was carried out for different corrugation profiles in the frequency bands around 60 GHz and 75 GHz.

In Fig. 4 the results of measurements for 2D Bragg resonators with sinusoidal and "chessboard" gratings are compared. Both resonators have the same geometry (*l_x=20 cm, l_z=18 cm, a_0=0.9 cm*) and corrugation period *d_x=d_z=0.4 cm*. Each resonator consists of one corrugated plate and smooth another one. The corrugation depth is 0.03 cm for sinusoidal and 0.02 cm for "chessboard" gratings which provides the same wave coupling coefficient $\alpha_{2D} \approx 0.07\ cm^{-1}$ for TEM wave scattering. As one can see, both structures give similar reflections. Thus, in the case of small depth the 2D sinusoidal corrugation is well approximated by the "chessboard pattern" corrugation.

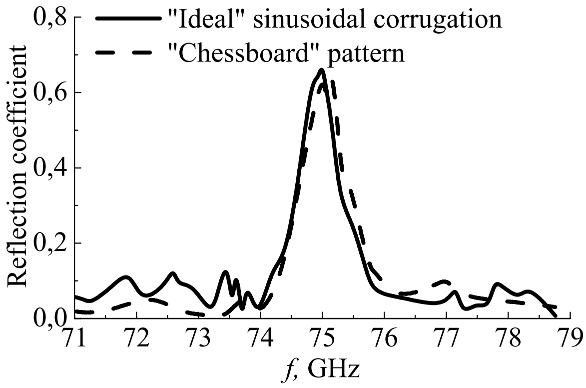

Fig. 4. Reflectivity of 2D Bragg resonators with "ideal" and "chessboard" gratings.

Spectral properties of 2D Bragg resonator with rectangular grooves corrugation obtained in "cold" measurements are presented in Fig. 5. In this resonator both plates are corrugated, $l_x=10$ *cm*, $l_z=18$ *cm*, $a_0=0.9$ *cm*. The corrugation depth is 0.03 cm. It is clearly seen that in accordance with theoretical predictions reflectivity is not symmetrical over the Bragg frequency (75 GHz) and shifted to the low frequencies. There is also an additional frequency zone near 77 GHz corresponding to the 1D Bragg scattering with the mode conversion $TE_{10}\leftrightarrow TH_{12}$.

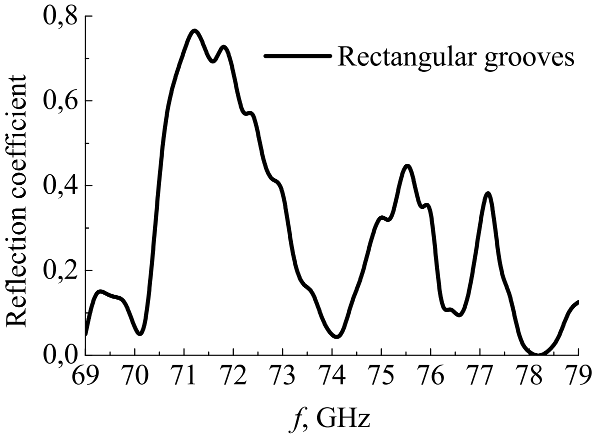

Fig. 5. Reflectivity of 2D Bragg resonators with "ideal" and "chessboard" gratings.

Properties of 2D Bragg resonators with various types of corrugation are discussed more detailed in [8] where the results of "cold" tests in frequency band near 60 GHz are also presented.

5. Bragg deflector

For the experiments at the ELMI-devise we have proposed the use of Bragg gratings for separation of a radiation and a high-current electron beam after the interaction region turning the output radiation to the transverse direction at the angle of 90º from the original longitudinal propagation [9]. This Bragg deflector consists of two gratings having a single-periodical shallow corrugation at the angle 45º with respect to the electron beam propagation.

According to simulations and "cold" measurements rectangular 10×10 cm Bragg deflector with a corrugation period 2.82 mm and depth 0.3 mm provides scattering into the transverse direction for the incident TE_{10}-wave in a waveguide with 10×1 cm cross-section with efficiency about 80% at the frequency band 74-76 GHz. However, the radiation profile after the scattering is a quite different from the profile of the incident mode. In Fig. 6 photo of the new designed deflector is presented. Geometry of the corrugated region allows profile of output radiation to be optimized for TE_{10}-wave output. This deflector with corrugation depth 0.4 mm provides ~90% RF-power output at the frequency band 73-78 GHz.

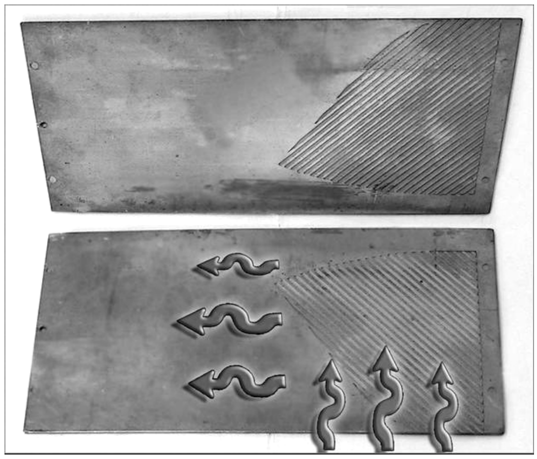

Fig. 6. Photo of the optimized Bragg deflector.

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