Demonstration of Mode Selection in Oversized Planar 2D Bragg Resonators

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Abstact − Electrodynamic properties of two-dimensional (2D) Bragg resonators of planar geometry realising two-dimensional distributed feedback are studied in the frame of the geometrical-optical approach and in 3D simulations. It was shown that the resonators possess high selectivity over both longitudinal and transverse mode indices and can be used in powerful microwave generators for provision of spatial coherence of radiation in strongly overmoded systems. Results of the theoretical analysis agree with the data obtained in "cold" microwave measurements at the frequency band of 60 GHz [1]. Transparency of the 2D Bragg structure in the vicinity of the Bragg frequency in the case of inclined wave-beam incidence has been observed. This effect corresponds to excitation of the fundamental eigenmode with the highest Q-factor. Direct 3D simulations also demonstrate high selectivity of 2D Bragg resonator and existence fundamental high Q modes nearby Bragg frequency.

1. Introduction

Two-dimensional (2D) Bragg structures of planar and coaxial geometries realizing 2D distributed feedback allows to develop the powerful sources of coherent mm radiation based on high-current relativistic electron beams of either sheet [2] and tubular [3] geometry. The first operation of the novel feedback mechanism in both FEM geometries was demonstrated recently [4,5].

The 2D Bragg resonators are modification of the traditional 1D Bragg structures, which were proposed for quantum [6, 7] and relativistic masers [8, 9] to realize 1D distributed feedback. The use of these structures, which in microwave band can be consisted of waveguide sections with shallow single-periodical corrugation providing coupling and mutual scattering of forward and backward (in the respect to the electron beam propagation) e.m. fluxes, allowed many successful experimental realization of high-power FEM-oscillators [9-12]. However such structures are able to provide mode selection only for the system transverse size of a few wavelengths. As a result, the output power produced in FEM exploiting 1D Bragg resonators did not exceed few tens of MW [9 - 12]. The novel 2D Bragg structures possess double- periodical corrugation in two-directions with the 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 synchronize radiation from different parts of a large-size electron beam. Computer simulations in the frame of geometrical-optical approach demonstrates possibility of generation of coherent mm radiation of a gigawatt power level in FEM when driven by electron beam of the transverse size up to 10^2 - 10^3 wavelengths and operating with 2D distributed feedback [2].

Present paper is devoted to detailed theoretical studies of electrodynamical properties of 2D Bragg structures of planar geometry. In difference with previous papers, where analysis was performed exceptionally in the frame of the geometrical-optical approach, in this paper we present 3D computer simulations which confirms results of analytical considerations. These results are proven also by the data obtained in "cold" tests of 2D Bragg structure having double periodical sinusoidal corrugation [1]. In accordance with theoretical analysis in these experiments the high-Q modes inside the Bragg scattering zone were observed. Existence of such modes in the middle of the Bragg scattering zone without any defects of periodicity is the specific feature of 2D Bragg structures in difference with traditional 1D structures [6 - 9], as well as photonic band gap structures [13, 14].

2. Basic model (geometrical-optical approach)

A planar 2D Bragg resonator consists of two metal plates (Fig. 1.) with the length l_z and width l_x, which are doubly corrugated as

$$a(x,z) = a_1 \cos(\bar{h}x)\cos(\bar{h}z) \, , \qquad (1)$$

where $2a_1$ is the corrugation depth, $\bar{h} = 2\pi/d$, d is the period over x- and z-coordinates. This structure provides coupling and mutual scattering of the four perpendicular-propagating partial waves

$$\vec{E} = \mathrm{Re}\Big[\vec{E}_0\left(A_+ e^{-i h z} + A_- e^{i h z} + \right. \left. + B_+ e^{-i h x} + B_- e^{i h x}\right) e^{i\omega t}\Big] \quad (2)$$

of the same transverse structure $E_0(y)$ if the wavenumbers h of the partial waves satisfy to the Bragg resonance condition (Fig. 2.):

$$h \approx \bar{h} \quad . \quad (3)$$

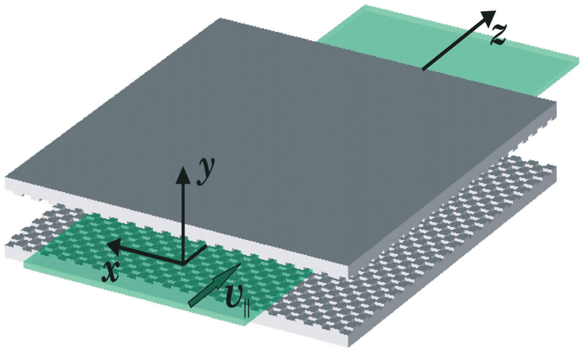


Fig. 1. Scheme of a planar 2D Bragg resonator.

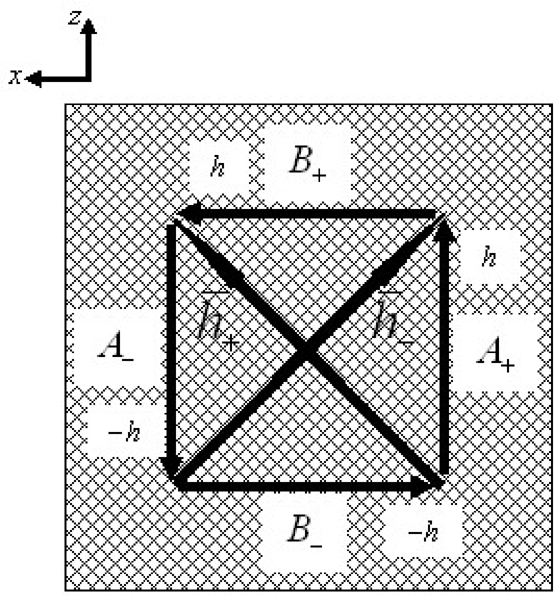


Fig. 2. Diagram illustrating 2D scattering of the four partial waves on the Bragg grating.

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_- completes the feedback cycle.

In the frame of the geometrical-optics mutual scattering of the four partial waves (2) may be described by the set of coupled-wave equations for the slow functions $A_\pm(x,z)$, $B_\pm(x,z)$ ([1]):

$$\begin{aligned} &\frac{\partial A_\pm}{\partial z} \mp i\delta A_\pm \pm i\alpha\left(B_+ + B_-\right) = 0 \\ &\frac{\partial B_\pm}{\partial x} \mp i\delta B_\pm \pm i\alpha\left(A_+ + A_-\right) = 0 \end{aligned} , \quad (4)$$

where $\delta = h - \bar{h}$ is the mismatch from the Bragg resonance (3) and α is the wave coupling coefficient, which for the case of scattering of the lowest propagating TEM-type partial waves has the form [1] $\alpha = a_1 h / 4a_0$.

3. Eigenmodes spectrum of a planar 2D Bragg structure

The spectrum of the resonator eigenmodes may be found from the solution of the Eqs.(4) under the assumption that the e.m. energy fluxes from outside the resonator are absent and the partial waves are not reflected from the edges of the resonator, which corresponds to the boundary conditions for the partial waves in the form:

$$\begin{aligned} &A_+(x,0) = 0, \quad A_-(x,l_z) = 0 \\ &B_+(0,z) = 0 \quad B_-(0,z) = 0 \end{aligned} . \quad (5)$$

An analysis of Eqs.(4) with the boundary conditions (5) shows that the 2D Bragg resonator possesses a spectrum of high-Q modes, which may be divided into two families, whose eigenfrequencies are located (a) near the Bragg resonance $\delta \approx 0$ and (b) near $\delta \approx \pm 2\alpha$. Under the conditions of strong wave coupling $\alpha l_{x,z} >> 1$ the solutions for the eigenmode frequencies $\omega_{n,m} \approx c\bar{h} + c\mathrm{Re}\delta_{n,m}$ and their Q-factors $Q_{n,m} \approx \bar{h}/2\mathrm{Im}\delta_{n,m}$ are given as [1]

$$\delta_{n,m} = \pm\frac{\pi^2 mn}{2\alpha l_z l_x} + i\frac{\pi^2}{2\alpha^2 l_z l_x}\left(\frac{n^2}{l_z} + \frac{m^2}{l_x}\right) \quad (6a)$$

near $\delta \approx 0$ and

$$\delta_{n,m} = \pm\left[2\alpha + \frac{\pi^2}{4\alpha}\left(\frac{n^2}{l_z^2} + \frac{m^2}{l_x^2}\right)\right] + i\frac{\pi^2}{2\alpha^2}\left(\frac{n^2}{l_z^3} + \frac{m^2}{l_x^3}\right) \quad (6b)$$

near $\delta \approx \pm 2\alpha$. According to (6) the 2D Bragg resonator possesses high selectivity over both the longitudinal (n) and the transverse (m) indices. This selectivity is originated from output of the radiation not only in the longitudinal $\pm z$ directions (similar to 1D Bragg resonators), but additionally in the transverse $\pm x$ directions. Solutions (6) are shown in Fig. 3 for parameters used in “cold” tests (see below). 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 $\{n = 1, m = 0\}$ (these modes for the case of $l_x = l_z$ are degenerated on the Q-factor). Spatial profiles of the partial waves forming the fundamental mode are shown in Fig.4.

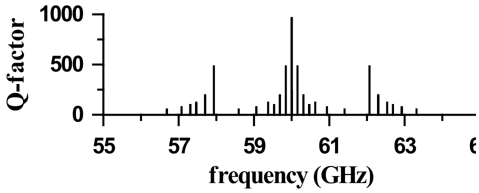


Fig. 3. Eigenmodes spectrum of 2D Bragg resonator.

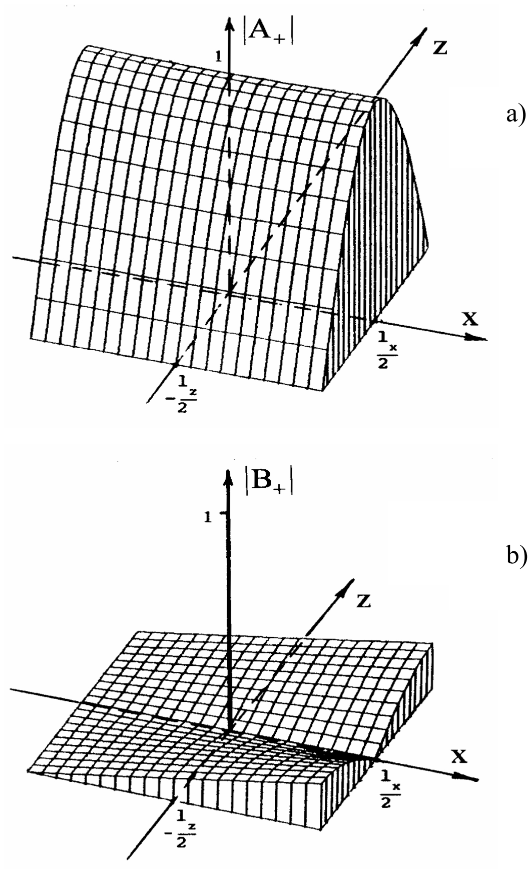


Fig. 4.
Spatial profiles of the partial waves forming the fundamental mode.

4. Simulations of excitation of 2D Bragg structures by an external wave

The frequencies and Q-factors of the resonator eigenmodes may be found also when modelling its excitation by a microwave beam coming in through one of the resonator edges. This modelling is necessary for interpretation of data obtained in "cold" resonator testing.

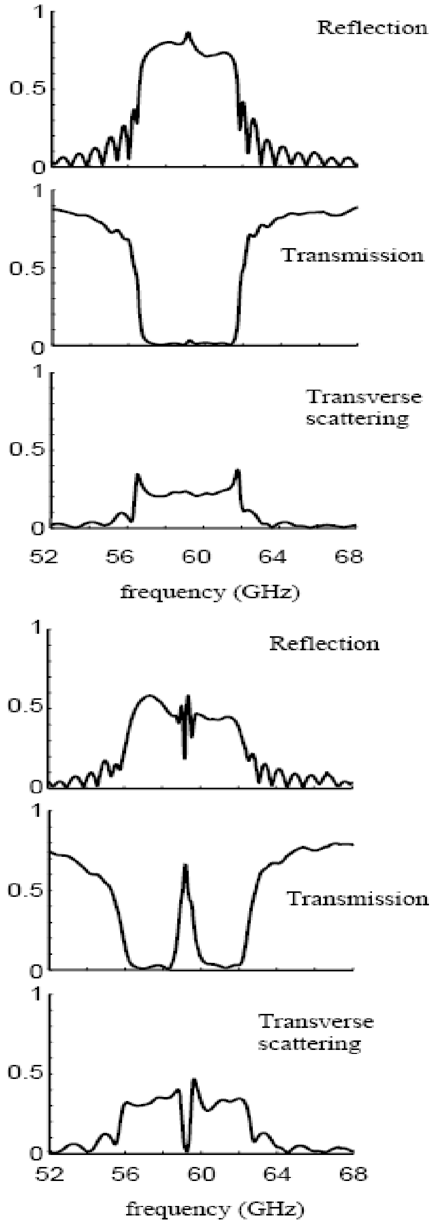
The simulation of excitation of a planar 2D Bragg resonator has been carried out also using the 3D code CST MicroWave Studio. To reduce simulation time the resonator was taken with $l_x = l_z = 15$ cm, i.e. a little smaller than used in the "cold" tests, but with deeper corrugation keeping the parameter $\alpha l_{x,z}$ constant. Results of simulations for different cases of the wave-beam incidence are shown in Fig. 5 and coincide well with the results obtained in the frame of the geometrical-optical approach.

To demonstrate selective properties of 2D Bragg resonators and the existence of a high-Q mode at the center of the Bragg reflection zone we exited the structure by a short (100 ps) incident e.m. pulse. In Fig.6a one can see the evolution of field amplitude at some point inside the structure. In Fig. 6b,c the frequency spectrum is shown for different time intervals. The position of the central line in the spectrum at the final stage of the decay process corresponds to the fundamental mode having the Bragg frequency and the spectrum width defines the Q-factor of this mode as $Q \sim 1000$, which coincides well with the value found in the theoretical analysis given above. Thus direct simulations also confirm high selective properties of 2D Bragg resonators under large Fresnel parameter.

5. Conclusion

For a Bragg structure of planar geometry analysis of the eigenmodes spectrum has been carried out in the frame of the geometrical-optical approach and direct 3D simulations based on the CST MicroWave Studio code. Both approaches demonstrate high selective properties of above structures for large Fresnel parameters. Scattering coefficients were found for the cases of normal and inclined incidence of the wave-beam. Frequency dependences of the scattering coefficients at the Bragg structure with 2D corrugation were simulated by the 3D code and coincide well with theoretical predictions. Theoretical and experimental investigations carried out demonstrated the performance of 2D Bragg structures and their high potential to be used as selective resonators for relativistic free electron masers.

a)



b)

Fig. 5.The 3D computer simulations of the reflection, transmission and scattering in transverse direction for the case of **(a)** symmetrical and **(b)** anti-symmetrical incident wave-beam.

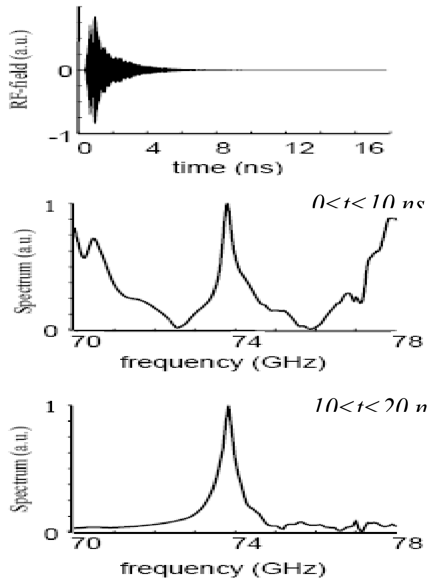


Fig. 6.Results of the 3D simulation of excitation of 2D Bragg resonator by short e.m. pulse: **(a)** time evolution of the RF-field and **(b), (c)** frequency spectrum for different time intervals of the decay process.

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