Three-dimensional analysis of coupled-cavity waveguides

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Abstract: A 3D finite-element analysis of Coupled Cavity Waveguides (CCW) shows the influence of the dielectric thickness and CCW length on transmission and losses.

1. Introduction

Photonic Band Gap (PBG) materials, also known as Photonic Crystals (PC), are periodic structures which exhibit a stop band for electromagnetic waves in a certain frequency range [1,2]. A "defect unit" within an otherwise perfect PBG is able to trap electromagnetic energy similar to a resonating cavity in the microwave world. A series of coupled defects then forms the equivalent of coupled resonators, and a miniband of transmission is opened within the "forbidden" band of the structure [3,4]. Such a series of defects, able to guide a wave in an integrated optical structure, is commonly referred to as a Coupled-Cavity Waveguide (CCW), and has been demonstrated at optical frequencies [5]. CCWs can be used in a variety of applications [4,6], including sharp bends and wavelength-selective waveguides and splitters. The demonstration of good transmission at microwave frequencies has confirmed this potential [7,8]. Recently, a new type of dispersion compensator based on a CCW waveguide has been proposed [9].

In integrated optics, a PBG structure can be constructed by creating a pattern of vertical holes in a dielectric layer on a chip. A CCW results when a regular series of holes in the periodic structure is not created, leaving the dielectric "as is" in those locations. Those locations form the "defects" mentioned above.

In this paper, we will study a CCW consisting of a chain of defects. Though it may seem appropriate to analyze this kind of CCW with two-dimensional methods, based on an effective index of refraction in every point of the dielectric, we will show that a full 3D analysis is necessary. We will study the radiative losses at the dielectric-air interface as a function of dielectric thickness and CCW length. All simulations have been performed with Ansoft's High-Frequency Structure Simulator (HFSS).

2. CCW Design

The dielectric material is GaAs with an index of refraction equal to 3.40, which is equivalent to a relative permittivity equal to 11.56, representing the most commonly used material for optical semi-ridged waveguides. The holes in the dielectric form a hexagonal

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lattice with lattice constant 400 nm and radius 140 nm. We define horizontal polarization as having the electric field vector perpendicular to the axes of the holes, i.e. in the plane of the dielectric layer. For horizontal polarization, the PBG structure shows a deep and wide band gap for both principal directions of propagation around 200 THz, i.e. around a free-space wavelength of 1500 nm. For vertical polarization, the band gaps for both principal directions don't coincide. Therefore, we will work with horizontal polarization.

The CCW is formed by not creating certain holes. Several choices can be made [10]; we skip one hole out of two in a particular direction, as shown in Fig. 1. This opens up the mini-band of transmission within the forbidden band of the PBG, as shown in Fig. 2.

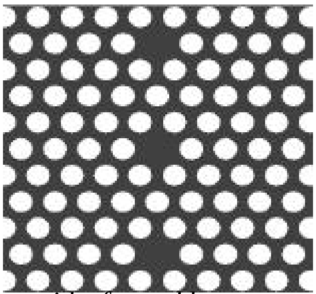

Fig. 1 The coupled-cavity waveguide, formed by not creating certain holes in the PBG

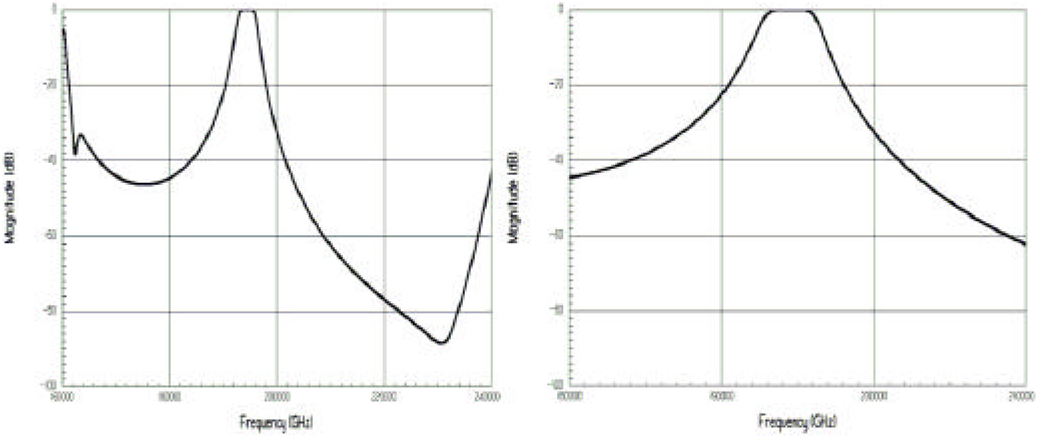

Fig. 2 The mini-passband, created by the defects, in the forbidden band of the PBG. Left: from 160 THz to 240 THz; right: a close-up of this from 180 to 210 THz. Vertical scale: magnitude S_{21} from -100 dB to 0 dB.

3. Influence of the dielectric thickness

For a 3-defect CCW of finite thickness, suspended in air, the S-parameters are strongly dependent on the thickness of the CCW. Fig. 3 shows the S_{21}-results for GaAs with thicknesses from 400 to 1000 nm. Note how the frequency shifts more as the thickness decreases. Also note that S_{21} is always well below 0 dB. Contrary to what may be expected, S_{21} does not improve monotonically with increasing CCW thickness. From 400 nm to 600 nm, the transmission improves with increasing thickness, but above 600 nm, it deteriorates again. The dominant loss mechanism is radiation. This shows clearly that a full 3D analysis is necessary.

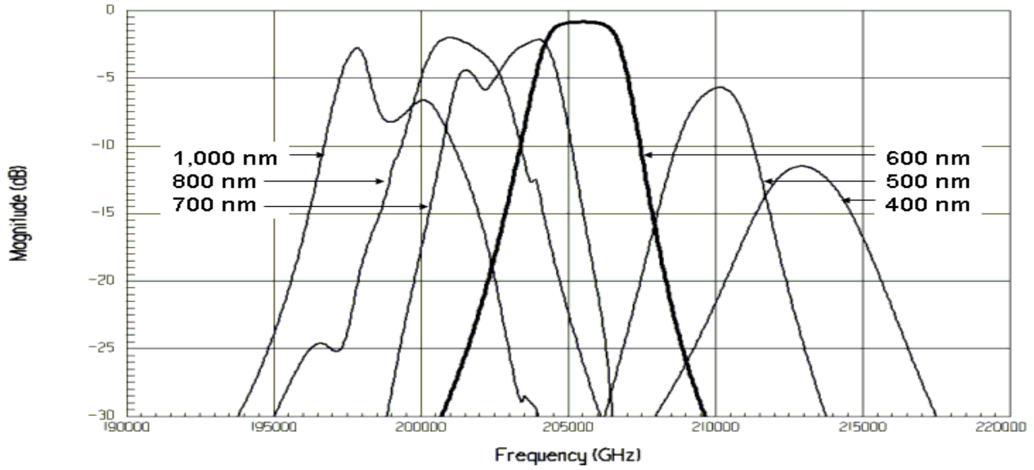

Fig.3 Full 3D analysis of a 3-defect CCWs for various thicknesses. From left to right, S_{21} for 1000, 800, 700, 600, 500, and 400 nm.

4. CCWs with more than three defects

With both the thickness of the dielectric and the coupling structure to a dielectric waveguide optimized for a CCW with three defects, CCWs with more defects are analyzed. Fig. 4 shows S_{21} curves for CCWs with five, seven and nine defects, coupled to waveguides at both ends.

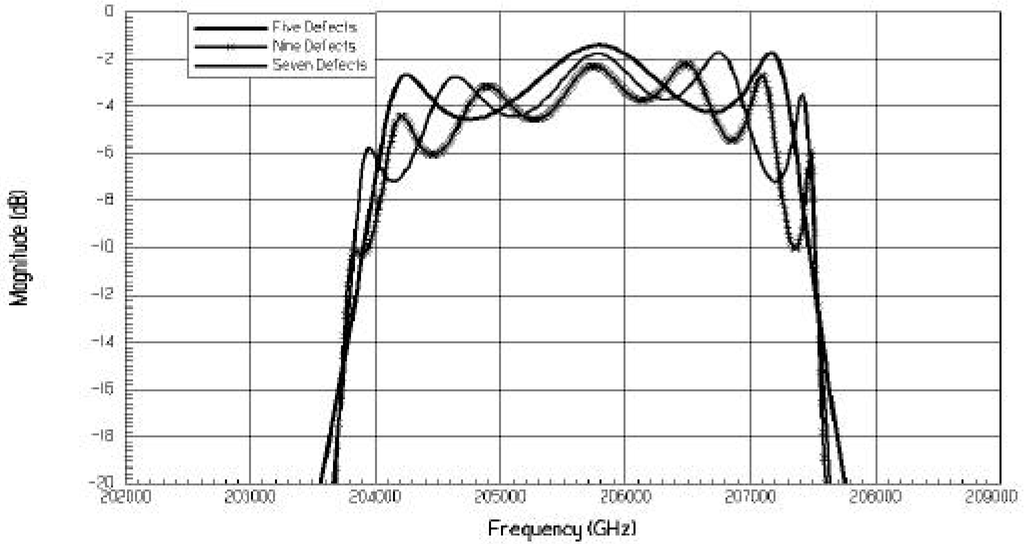

Fig. 4 S_{21} for system of waveguides and a CCW with five (fat line), seven (thin line) and nine (fuzzy line) defects.

Note that the bandwidth remains rougly the same as the number of defects increases, as it is determined mostly by the coupling between the defects. The ripple in the pass band is very large, on the order of 2 dB. There is a correspondingly large ripple in S_{11}. This indicates that a much better coupling structure to the waveguides is needed. Further note that as the number of defects, and thereby the length of the CCW, increases, the maximum

S_{21} decreases. This is due to radiation. The table below lists the percentage of the input power that is lost to radiation at 205.75 THz, the frequency of maximum transmission. Note that the radiation losses increase almost linearly with the number of defects.

Number of defects in CCW	Radiation (% of input power)
3	15.2
5	22.0
7	29.1
9	35.5

5. Conclusions

For the design and analysis of coupled-cavity waveguides and their coupling to ridge waveguides, a 2D analysis based on effective index of refraction is insufficient. The 3D finite-element analysis in this paper has shown how the individual “defects” in the CCW radiate into space, and how this depends on dielectric thickness. Coupling with a dielectric waveguide was optimized for a CCW with three defects, but longer CCWs still had a large ripple in the pass band. Since CCWs consist of coupled resonators, they show similarities to Chebychev band-pass filters. Design techniques for such filters may be helpful to design CCWs.

6. References

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