Design Sensitivity in Quasi-One-Dimensional Silicon-Based Photonic Crystalline Waveguides

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Abstract

This paper describes how the optical properties of a quasi-one-dimensional photonic crystalline waveguide having a periodic air cavity are influenced by various structural parameters; the electromagnetic fields are simulated using the finite-difference time-domain method. The simulations considered four design parameters: cavity size, defect size, lattice constant, and number of cavity. The parameter sensitivity of the photonic bandgap property of the waveguide having air cavities is examined. A couple of significant design guidelines are obtained. We show that the quasi-one-dimensional photonic crystalline waveguide has significant unrealized potential.

1. Introduction

The increasing scale of integrated Si devices has given rise to a significant increase in the signal delay time between circuit blocks; the signal delay time is now much longer than the gate delay time of individual devices. It was hoped that this difficulty could be overcome by an advanced metallization technique that replaces Al-based wires with Cu-based wires and the SiO_2-based interlayer dielectrics with a low-κ dielectric material. However, it is anticipated that the propagation delay time of interconnections will still determine the speed of integrated circuits when the gate length falls under 0.18 μm. This problem may be overcome by setting optical links between circuit blocks in a chip or LSIs to transfer signals. Silicon-based waveguides have been widely studied from the viewpoints of monolith circuits and process compatibility [1]. The designs must allow for problems such as sharp bends, mode dispersion, and specific attenuation.

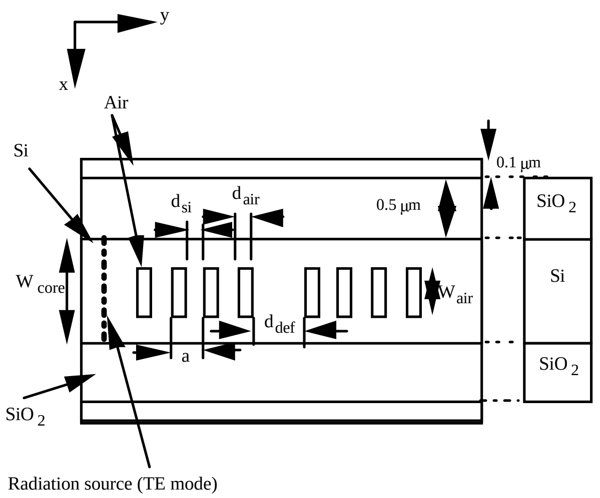

Figure 1. Waveguide top view. Notations of devices parameters are defined.

Against this background, photonic crystalline (PC) materials are attracting attention for controlling lightwave transmission [2]; photonic bandgap (PBG) structures are especially useful in applications where the spatial localization of lightwaves is required [3]. In a three-dimensional (3-D) PC, we can control the propagation of lightwaves in all directions. Generally speaking, however, it is very difficult to fabricate 3-D PC structures. Its simpler cousin, 1-D PC, offers significant easier fabrication at the cost of reduced functionality. Recently, the influence of defects in 1-D PC waveguides with periodic air cavities has been demonstrated experimentally and the characteristics of such waveguides have been verified by simulations [4]. However, it has not been clarified how design parameters, such as the shape and dimensions of the air cavities, affect the characteristics of the 1-D PC waveguide.

This paper describes how the design parameters of a quasi-1-D PC structure influence its lightwave transmission characteristics. The transmission coefficient is simulated by the finite-difference time-domain (FDTD) method [5] as implemented in a commercial device simulator [6]. Here we assume that the lightwaves have the wavelength (λ) of 1.55 μm because it is representative of modern optical communications systems.

2. Device structure and simulation method

We consider a quasi-1-D PC waveguide. The waveguide has a 0.49-μm-wide silicon core (W_{core}) with periodic air cavities and 0.5-μm-thick SiO_2 cladding as shown in Fig. 1, where a is the lattice constant; the figure shows a top view of the waveguide. A break in the periodicity of the air cavities introduces a defect into the quasi-1-D PBG; the defect is allocated in the center of waveguide as shown in Fig. 1. Electromagnetic fields are found by solving Maxwell's equations using the FDTD method. The cell size for computations is $\Delta x=\Delta y=5$ nm. Since we carry out 2-D simulations of electromagnetic fields, it is implicit that the waveguide has infinite depth. We use a perfect-matching layer at the computational cell edges. The built-in electromagnetic source radiates a Gaussian-

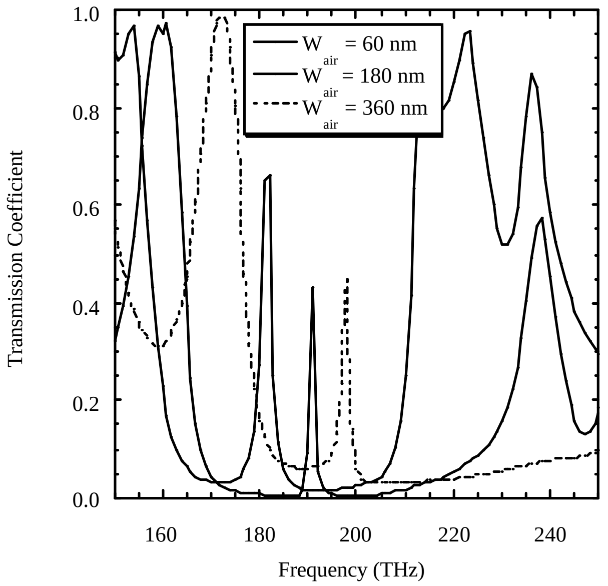

Figure 2. Transmission coefficient dependence on frequency for various air cavity widths.

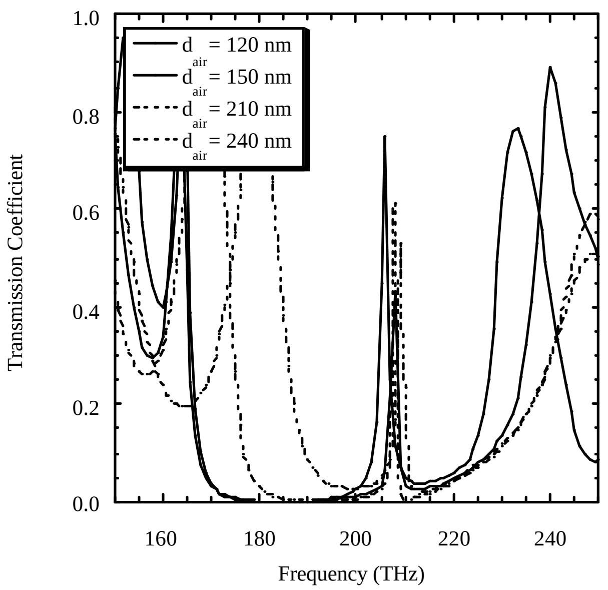

Figure 3. Transmission coefficient dependence on frequency for various air cavity lengths.

shape wave packet that is modulated over time by a sinusoidal wave; the wave packet has the center frequency of 193 THz. We calculate the transmission coefficient through a waveguide with periodic air cavities; the locations of plane1 (radiation source) and plane2 (observation of transmitted wave) are set appropriately as shown in Fig. 1. Before characterizing the qausi-1-D PC waveguide, we examined the basic propagation property of the waveguide without any air cavities. We found stable lightwave propagation in the frequency range of 90 to 270 THz, which means that a lightwave with λ of 1.55 μm (~200 THz) can transit this waveguide.

3. Simulation results and discussion

3.1 Fundamental parameters for consideration

In the following discussion, spatial coordinates are normalized by the lattice constant (a) and the angular frequency (ω) is normalized by c/a, where c is the velocity of light in a vacuum. In this sense, the solutions of Maxwell's equations are in themselves independent of the lattice constant, and basically we should be able to discuss PBG characteristics regardless the frequency in the frequency range from microwaves to ultraviolet light. However, the structure shown in Fig. 1 has a silicon core with fixed width (W_{core}), so the lattice constant is still one of the design parameters. Thus, we consider the impact of design parameters (cavity size, defect size, lattice constant, and number of cavities) on PBG characteristics.

3.2 Influence of air cavity size (W_{air} x d_{air})

Transmission coefficients were calculated for various values of W_{air} in the range of 30 to 490 nm, while the other design parameters are fixed; a= 300 nm, air cavity spacing (d_{si}) = 120 nm, air cavity length (d_{air}) = 180 nm (d_{si}/d_{air}=2/3), and defect length (d_{def}) = 550 nm. In Fig. 2, simulated transmission coefficients are shown as a function of frequency for the cases of W_{air}= 60, 180, and 360 nm.

As W_{air} increases, the transmission-inhibited band and the frequency of the defect-induced transmission mode shift to a higher frequency range. When W_{air} is designed to range from 120 to 180 nm (W_{air}/W_{core} ranges from 0.245 to 0.367), the transmission coefficient of the transmission-inhibited band has a smaller value than that for W_{air}= 60 or 360 nm. This suggests that there is an optimal value of W_{air} that yields the smallest transmission coefficient.

Transmission coefficients were calculated for various values of d_{air}. Simulated transmission coefficients are shown in Fig. 3 as a function of frequency. Since the value of a was fixed, the value of d_{si} was varied automatically. Since the value of d_{air} ranged from 0.1a to 0.9a in simulations, the value of d_{si} ranged from 0.9a to 0.1a. The other design parameters were fixed; a= 300 nm, W_{air} = 180 nm, and d_{def} = 550 nm. In Fig. 3, typical transmission coefficients are shown as a function of frequency in the d_{air} range from 0.4a to 0.8a. As shown in Fig, 3, as the ratio of d_{air} to a increases, the transmission-inhibited band is shifted to a higher frequency range. The frequency of the defect-induced

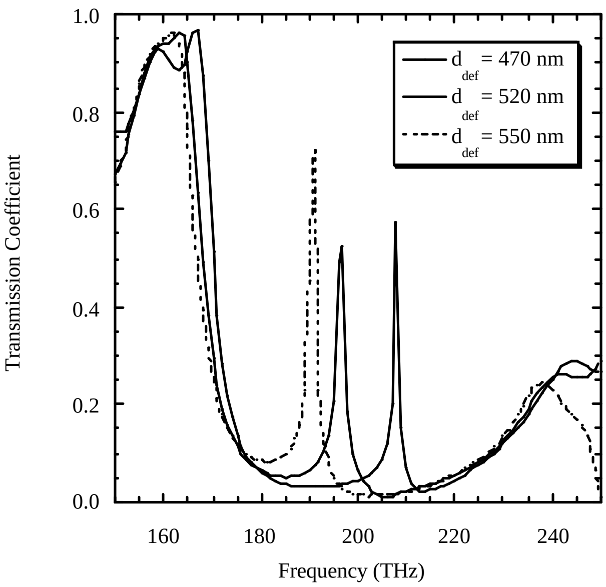

Figure 4. Transmission coefficient dependence on frequency for various defect lengths.

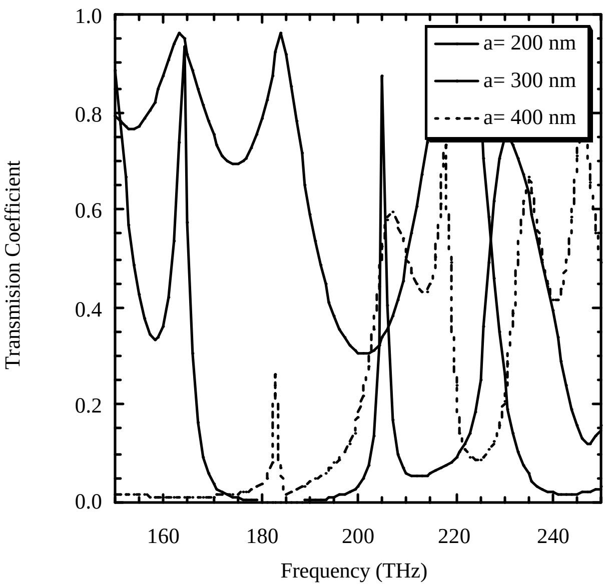

Figure 5. Transmission coefficient dependence on frequency for various lattice constants.

transmission mode also is raised. However, the frequency of the defect-induced transmission mode is quite insensitive to the ratio of d_{air} to a for 0.5a < d_{air} < 0.7a. For d_{air} < 0.5a or d_{air} > 0.7a, transmission coefficients are larger than those for 0.5a < d_{air} < 0.7a. The transmission coefficient is smallest for d_{air} values from 0.6a to 0.7a.

3.3 Influence of defect size

Transmission coefficients were calculated for various values of d_{def}. Simulated transmission coefficient versus frequency is plotted in Fig. 4. The assumed d_{def} values were 470, 520 or 550 nm while the other design parameters were fixed; a= 300 nm, d_{si} = 120 nm, d_{air} = 180 nm (d_{si}/d_{air}=2/3), and W_{air} = 180 nm. As d_{def} increases, the frequency of the defect-induced transmission mode falls while that of the transmission-inhibited band drops only slightly. The bandgap width and the transmission coefficient inside the bandgap are insensitive to d_{def}. A 10-nm variation in d_{def} results in a 2 to 3 THz variation in the frequency of the defect-induced transmission mode (15 to 20 nm in the wavelengh).

3.4 Influence of lattice constant

The frequency dependence of the transmission coefficient was calculated for various lattice constants as shown in Fig. 5. Lattice constant, a, was varied from 200 to 400 nm while the other design parameters were fixed; d_{si} = 0.4a, d_{air} = 0.6a (d_{si}/d_{air}=2/3), and W_{air} = 180 nm. As a increases, the transmission-inhibited band dramatically shifts to a low frequency and the bandgap width increases.

As mentioned in section II, the stable propagation of lightwave is limited to frequencies from 90 to 270 THz. When a = 200 nm, the frequency of the defect-induced transmission mode is higher than 270 THz; the simulation result for a = 200 nm is thus not reliable for the present consideration. The simulation results indicate that the optimal value of a is about 300 nm for W_{core} = 0.5 μm.

3.5 Effects of number of cavity

It is known that increasing the number of cavities yields a high quality factor from the analogy of a microwave resonator. Here, we examine how cavity number impacts PBG characteristics. As shown in Fig. 6, transmission coefficients were calculated as a function of frequency for four cavity numbers (4, 6, 8 and 10), while the other design parameters were fixed; a= 300 nm, d_{si} = 120 nm, d_{air} = 180 nm (d_{si}/d_{air}=2/3), W_{air} = 180 nm, and d_{def} = 470 nm. As the cavity number increases, PBG width slightly decreases and the transmission coefficient inside the bandgap decreases.

In this study, the thickness of the Si core is infinite because of the 2-D simulation. For a Si core with finite thickness, the predicted transmission coefficient would be larger than the present simulated value [7].

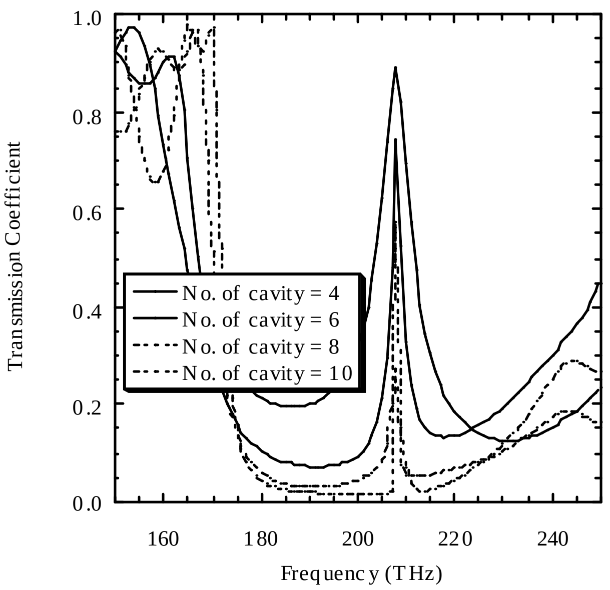

Figure 6. Transmission coefficient dependence on frequency for various air cavity numbers.

4. Conclusion

We used the FDTD method to simulate the electromagnetic fields of a quasi-1-D optical waveguide with periodic air cavity. The design parameters considered were cavity size, defect size, lattice constant, and number of cavities. We examined the impact of the parameters on the PBG property of the waveguide.

There is an optimal air cavity width that yields the smallest transmission coefficient. When the ratio of air cavity length (d_{air}) to lattice constant (a) increases, the frequency of the defect-induced transmission mode also increases. However, the frequency of the defect-induced transmission mode is quite insensitive to the ratio of d_{air} to a for $0.5a < d_{air} < 0.7a$. As defect length increases, the frequency of the defect-induced transmission mode falls. PBG width and transmission coefficient inside the PBG are insensitive to defect length. As the cavity number increases, PBG width slightly decreases and the transmission coefficient inside the PBG decreases as expected.

These results indicate that the quasi-1-D PC waveguide has a bright future since it is easy to fabricate them in comparison to 2-D or 3-D PC waveguides,

Acknowledgement

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