Optical Filters from Photonic Band Gap Air Bridges

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Abstract— **Surrounding waveguides by air reduces radiation losses so the air bridge geometry can produce optical filters with sharp transmission resonances and very wide stop bands.**

I. INTRODUCTION

IN recent years, photonic band gap materials have attracted much attention. What makes such materials special are wide band gaps or stop bands—ranges of frequencies where no light can propagate. Waves incident on these materials will be reflected if their frequency lies within the gap; the fields decay exponentially inside the material. Possible applications of these unique properties are laser cavities with low thresholds, efficient radiation from planar antennae, and microbends with low loss [1]–[5]. Imperfections in fabrication do not appear to affect these photonic properties significantly [6].

Here we give quantitative description of the filter properties of these structures. For simplicity we study a one dimensional band gap. Conventional gratings may have index modulations of only a few percent. In contrast, photonic band gap materials have large index contrasts typically, as large as of 3:1. This large index ratio or contrast leads to a wide stop band. But as the index contrasts or grating strengths become larger, the fields tend to radiate out of the waveguide. To confine the light, we can surround the waveguide by a lower index material or by a photonic band gap material. In this case, we use air, forming an air bridge (Fig. 1). Since interfaces between air and high dielectric material confine light well, we are able to design an optical filter (Fig. 1) whose transmission resonance peaks at 91%. And since the index contrasts are so large, the stop band width is about 40% of the carrier frequency! We also present a second filter with a very sharp transmission resonance, whose quality factor "Q" exceeds 24 000. In this paper, we will first describe how we model these filters, then present more details on the characteristics of these novel filters.

II. METHOD

We calculate the transmission, reflection and radiation spectrum by a finite difference-time domain program. Such programs are reviewed by Miller [7]. Since the index contrasts are so large, analytic methods like coupled mode theory are

not as accurate. We need to turn to numerical techniques. Specifically, we integrate Maxwell's equations forward in time over the two spatial dimensions:

$$\nabla \times E = -\mu \frac{\partial H}{\partial t}$$
$$\nabla \times H = \epsilon \frac{\partial E}{\partial t}.$$

For accuracy, the electric E and magnetic H fields are separated by half steps in space and time, in a Yee lattice [8]. This initial value problem is explicit; the fields at one time step depend only on the fields at the previous time step. As a result, such schemes can be run efficiently on parallel computers [9].

In such programs, the boundary conditions tend to be the most challenging part. The treatment of the outer boundary (unbounded space) is of particular importance. The popular absorbing boundary condition [10] suffers from reflections from the computational border. These spurious reflections become particularly severe in microstrip line simulations, where the indexes of refraction changes along the border. Over the years, many schemes have been devised to minimize these reflections [11]–[13]. The recently reported Berenger's perfectly matched layer (PML) [14] gives low reflections, even for microstrip lines [15]. To achieve such low reflections, researchers [14] and [15] increase the conductivity or absorption strength or the matching layers quadratically, with a power of $n = 2$. However, Chen and Li [16] find that significant further improvement can be achieved by using quartic gradations ($n = 4$). Following this example, we choose our layer to be $\delta = 12$ grid points thick, which has a theoretical reflectivity of $R(\theta = 0) = 10^{-6}$ in free space. Inside the dielectric, the conductivity is multiplied by the dielectric constant [15]. These low reflections eliminate the Fabry–Perot fringes that would otherwise arise from the reflections at the grating region and the computational boundary [16].

One can use a sine wave source to calculate the transmission and reflection at one frequency [17]. However, pulsed sources are more efficient for calculations over a range of frequencies. In particular, one can send in a Gaussian source to the filter and monitor the reflected and transmitted pulses. The fast Fourier transform (FFT) of these pulses, normalized to the spectrum of the input pulse, gives the reflection and transmission spectrum. In our simulations, we send in a Gaussian pulse whose pulse width equals the period $1/f$.

$$\sin\left(2\pi ft\right) \exp\left[-(ft - 4)^2\right], \quad t \geq 0.$$

This gives sufficient frequency range to model the filters.

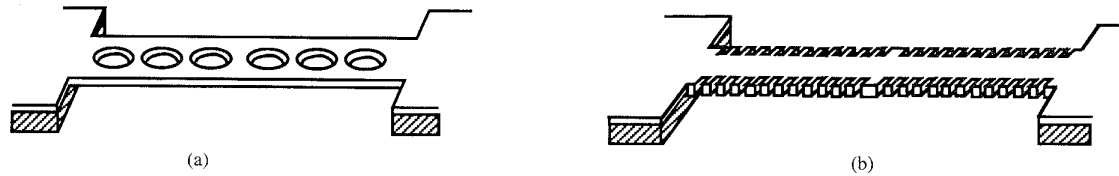(a)   (b)

Fig. 1.   (a) Schematic of air-bridge with six circular holes and (b) another bridge with 33 notches.
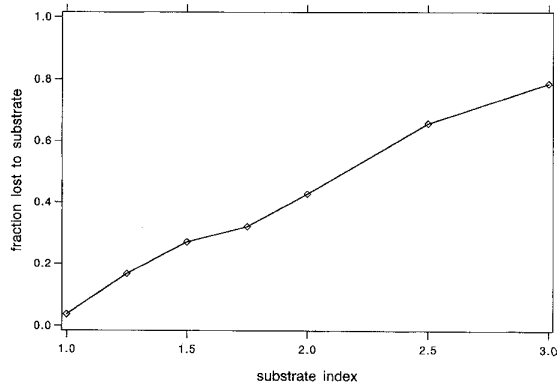

Fig. 2.   Fractional power lost to substrate as a function of substrate index.

We can also obtain physical insight about the transmission peak, by examining the resonator properties. The energy of a resonator decays exponentially.

$$W = W_0 e^{-\omega_0 t/Q}$$
$$= W_0 e^{-2t/\tau}$$

where $Q = \omega_0 \tau/2$ is the quality factor, ω_0 is the resonance frequency, and τ is the decay constant. Using coupled mode theory, Haus [18] calculated the transmitted power through a resonator

$$T_{pwr} = \frac{\dfrac{4\tau^2}{\tau_{e1}\tau_{e2}}}{(\omega - \omega_0)^2\tau^2 + 1}$$

where τ_{e1} measures the decay of fields into the external world or waveguide from port 1. Since our filters have symmetry input and output ports, τ_{e1} and τ_{e2} are equal and can be combined into an overall external decay constant $\tau_e = \tau_{e1}/2$. This simplifies the transmission to

$$T_{pwr} = \frac{\left(\dfrac{\tau^2}{\tau_e}\right)^2}{(\omega - \omega_0)^2\tau^2 + 1}.$$

This transmission expression considers the input coupling between the waveguide and the resonator, the intrinsic radiation losses of the resonator and the output coupling of power to the waveguide. The maximum transmission is $T_{pwr}(\omega = \omega_0) = (\tau^2/\tau_e)^2 = (Q^2/Q_e)^2$ where Q_e is the external quality factor. The external quality factor measures the rate at which energy is transferred from the resonator cavity to the external waveguides. Specifically, $Q_e = \omega\tau_e/2$ is the number of cycles needed for the resonator energy to decay to $1/e^{2\pi}$. The ratio
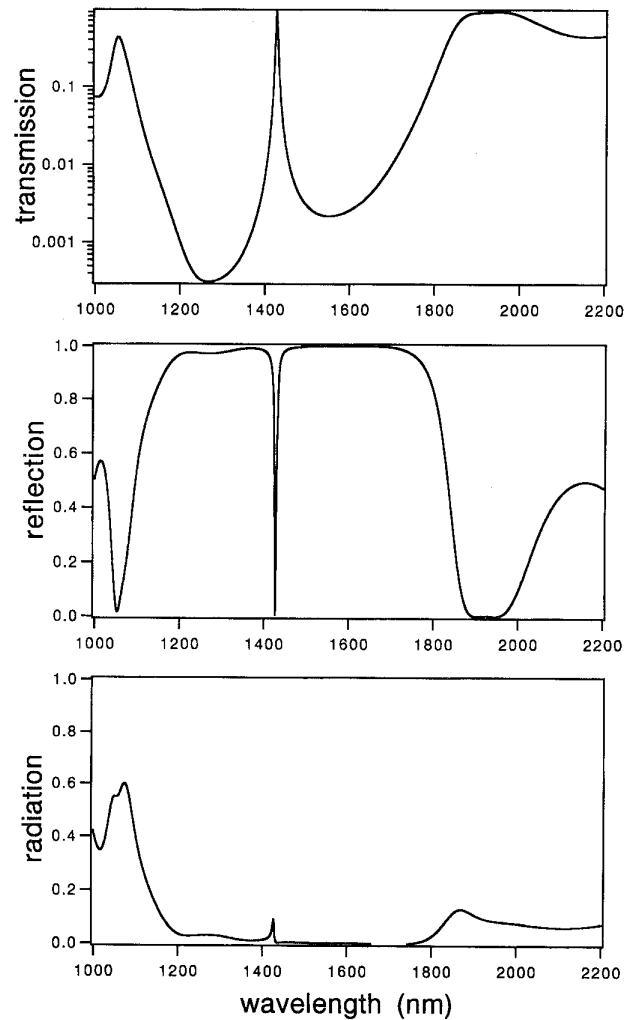

Fig. 3.   Power transmitted, reflected and radiated as a function of wavelength.

of the resonance frequency and the full width half maximum (FWHM) of this transmission resonance is

$$Q_{\mathrm{FWHM}} = \frac{\omega_0}{\dfrac{2}{\tau}}$$
$$= \frac{\omega_0\tau}{2}$$
$$= Q_{\mathrm{resonator}}.$$

This suggests that from the transmission peak, one can predict such resonator parameters as ω_0, Q, and Q_e.

We calculate such parameters using the finite difference time domain method. To extract the quality factors, we need
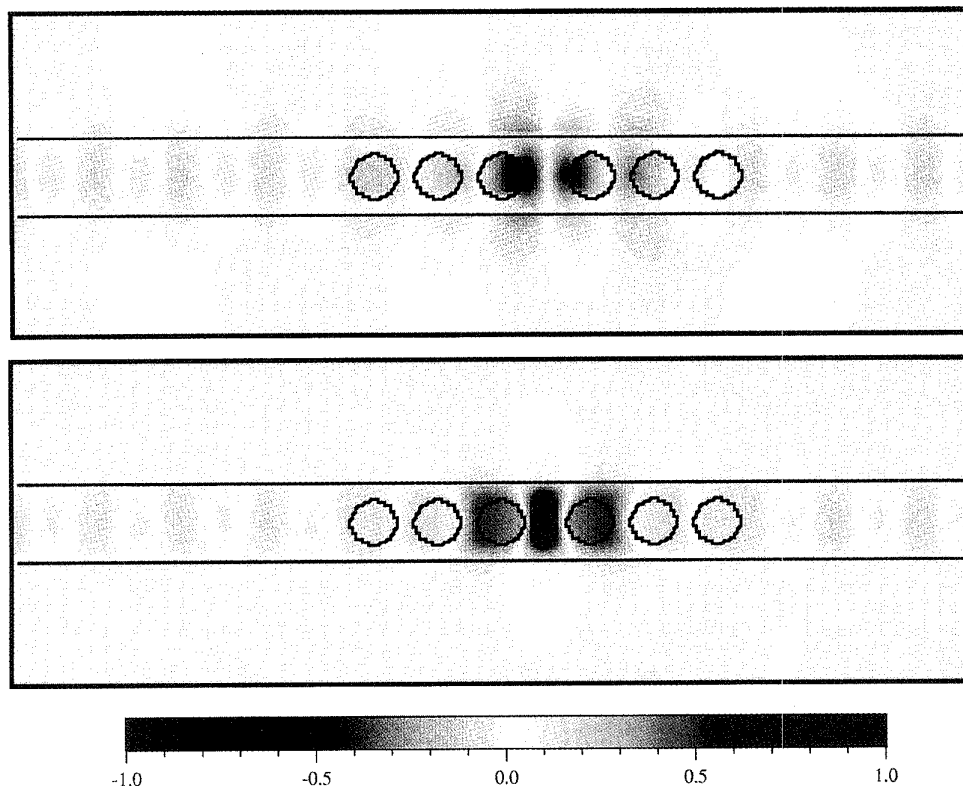
Fig. 4. Top panel: Electric field component lying in the page and transverse to the propagation direction, at transmission resonance. Bottom panel: Magnetic field normal to the page at transmission resonance.

to excite that resonator eigenmode. An arbitrary initial field can be decomposed into many eigenmodes, each of which decays exponentially with a rate ω/Q. A sufficiently long propagation will yield the mode with the largest Q; the other eigenmodes will be negligibly small [19]. Of course, this calculation can be speeded up if the initial field resembles the high Q eigenmodes. By monitoring the rate of energy decay, we obtain the Q of the eigenmode. The resonance frequency ω_0 comes from the oscillation rate of the electric or magnetic field.

So, by knowing the resonator properties, we can predict some features of the transmission. There is good agreement between the two.

III. RESULTS

The optical filters we wish to investigate are air bridges (Fig. 1). The air surrounding the waveguide on all four sides—top, bottom, left, and right—helps to confine the light inside the bridge waveguide. This suppresses the radiation losses, giving a high Q resonator and a narrow transmission resonance peak. To illustrate this point, let us examine what happens if the air were replaced by another material on just one side. We will perform a 2-D model of an air bridge, by focusing only on its crossection. The air bridge shown in Fig. 1(a) has six air holes, which are spaced 0.232 free-space wavelengths λ or (for $\lambda = 1.55\,\mu$m) 0.360 μm apart. This hole-to-hole separation increases to 0.325λ or 0.503 μm for the center two holes, giving rise to the quarter wave-

like phase shift that gives the transmission resonance. The diameter of each hole is 0.167λ or 0.258 μm. The entire structure is only 1.420λ or 2.20 μm. This small size allows for a compact integration of many wavelength filters on a small chip. A slightly longer version of this structure—one with more air holes—can act as a high Q microcavity [17], [19], and [20]. Others have constructed microcavities using whispering gallery modes [21]. Our waveguide has a rather narrow width 0.281λ or 0.435 μm, so they are very difficult to couple into. In practice, an adiabatic taper would be needed to improve coupling efficiency. We choose the core index to be $n = 3.4$ because it is close to the indexes for GaAs and Si. Now, if we place AlAs next to the waveguide, about 80% is radiated into the AlAs slab. So, even an index contrast of 3.4:2.8 is not enough to confine the light (Fig. 2). The radiation loss drops dramatically as the index becomes lower. For air ($n = 1$) the loss to that one side becomes almost negligible. For more details on how this calculation is performed, see [17].

Fig. 3 plots the transmitted and reflected power as a function of wavelength. Notice the reflection is almost unity over a 600 nm range. This is about 40% of the carrier wavelength! The Q or ratio of the carrier wavelength to the transmission FWHM is 264.7. The radiation loss is near 0, over most of the range. At lower wavelengths, however, radiation increases as light is coupled to higher order transverse modes. Fig. 4 shows the electric field (pointing down) and the magnetic field (pointing out of page) at transmission resonance. Coming in from the
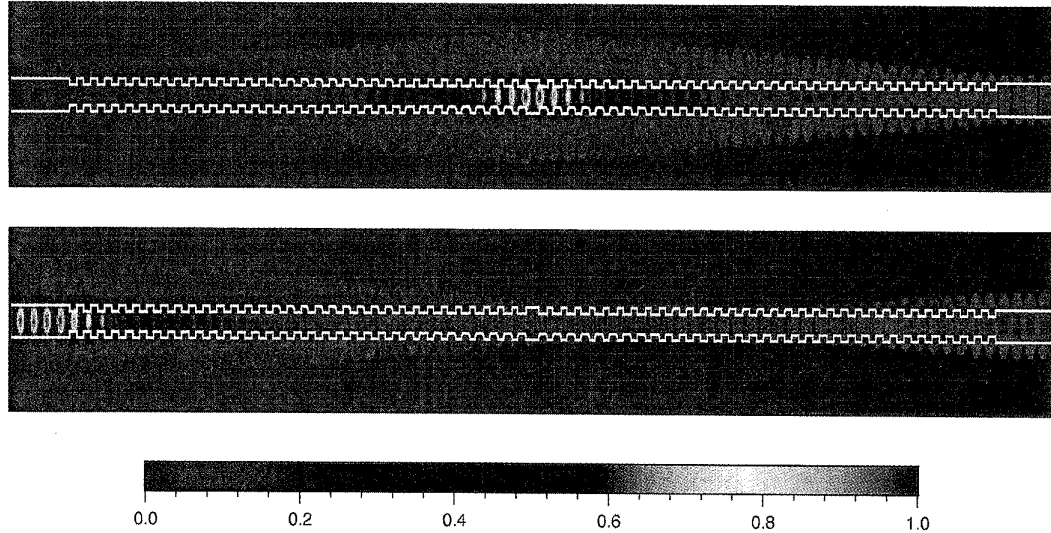
Fig. 5. Top panel: Absolute value of electric field normal to page, at transmission resonance. Bottom panel: Absolute value of magnetic field lying in the page and transverse to the propagation direction, at transmission resonance.

left side of the figure, light is coupled to the resonator mode in which most of the light is localized about the so-called quarter wave phase shift or dielectric defect. Then over 91% is transmitted to the other side! This air bridge geometry allows a wide stopband and a large transmission. And most of the light is confined to the waveguide.

By measuring the energy decay of the resonator, we find the quality factor of 269.6. This compares favorably to the $Q = 264.7$ obtained from the transmission width. Since at resonance, the maximum transmitted power is $T_{pwr} = 0.911\,74$ and $T_{pwr} = (Q/Q_e)^2$, then $Q_e = 1.0473Q = 282.3$. The estimated radiation quality factor is $Q_r = 1/(1/269.6 - 1/282.3) = 5993$, using

$$\frac{1}{Q} = \frac{1}{Q_r} + \frac{1}{Q_e}.$$

We present another filter with an even larger "Q." By omitting the holes and by notching the sides of the air-bridge instead [Fig. 1(b)], we reduce the index contrasts or grating strengths. This reduces the stop band width. More importantly, this also lowers the radiation losses. Specifically, the stop band width falls to 70 nm. Note that for optical communication purposes, this width is more than adequate, being about double the gain bandwidth of erbium amplifiers. The quality factor is much larger than before; Q exceeds 20 000. The notches are 0.0356 free-space wavelengths deep and 0.0888 wavelengths long. Notches are separated from each other by 0.178 wavelengths. As before, we choose an index of 3.4 for the bridge. It is 0.195 wavelengths wide and 11.812 wavelengths long. There are 33 notch pairs on each side of the phase slip, which measures 0.178 wavelengths long. Fig. 5 shows the absolute values of the electric field (normal to page) and the magnetic field (in the page but normal to propagation direction). The transmitted, reflected, and radiated powers are shown in Fig. 6. Note the sharpness of the transmission peak at resonance. There are only a few data points in the center of this resonance. Calculating more points would require much
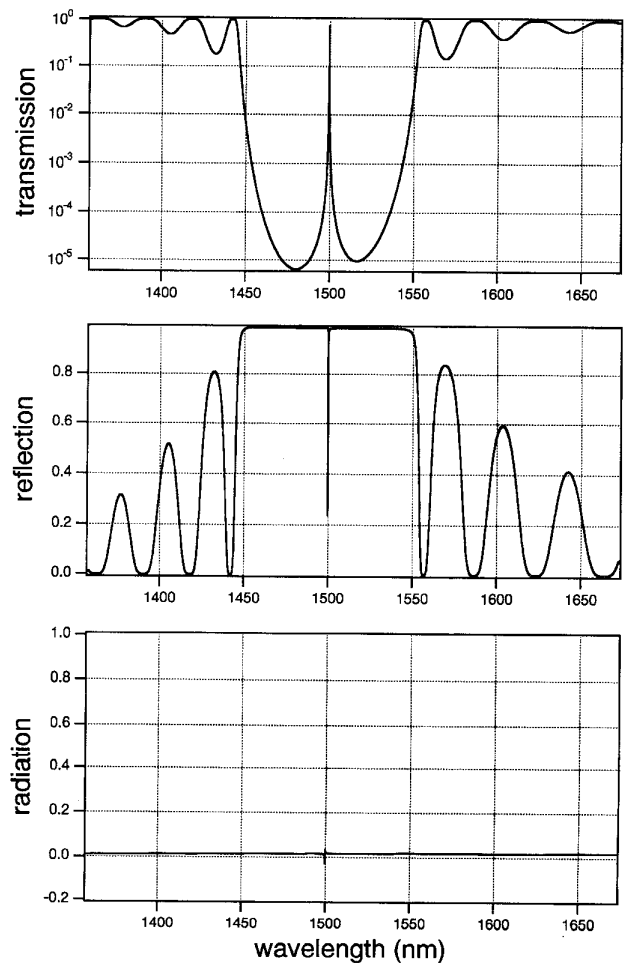

Fig. 6. Fraction of power transmitted, reflected, and radiated by notched filter as a function of frequency.

computer time. From these points, the quality factor must exceed 11 000. From the energy decay, we find a "Q" of

24 100. The highest transmitted power observed is 0.741. This corresponds to a radiation "Q" of over 173 000! Moving off resonance, the transmission falls by 40 dB. As a result, another filter with a slightly different transmission resonance would see very little crosstalk.

In conclusion, we have presented optical filters based on air bridge geometries. The suppression of radiation leads a large transmissions. The large index modulations give enormous stop bands whose widths are about 40% of the carrier wavelength. We can also achieve "Q"s of over 24 000, resulting in very sharp transmission resonances.

ACKNOWLEDGMENT

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