Wide-field-of-view narrow-band spectral filters based on photonic crystal nanocavities

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We describe a novel approach to implementing wide-field-of-view narrow-band spectral filters, using an array of resonant nanocavities consisting of periodic defects in a two-dimensional three-material photonic-crystal nanostructure. We analyze the transmissivity of this type of filter for a range of wavelengths and in-plane incidence angles as a function of the defect's refractive index, the number of layers in the photonic-crystal reflectors, and the period of the defects and find that this structure diminishes the angular sensitivity of the resonance condition relative to that of a standard multilayer filter.

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Optical frequency-selective filters based on thin-film technology have been investigated for a broad range of applications. However, for some applications, the strong coupling between the incidence angle and the resonance wavelength in a thin-film filter poses technical challenges, for example, in a free-space communication link in which the transmitter and receiver are mobile and their relative positions are unknown. For this type of application, in which a wide-field-of-view narrow-bandpass filter is desirable, we investigate a novel approach based on quasi-two-dimensional resonant microcavities formed by the introduction of periodic defects into a two-dimensional (2D) photonic crystal structure.

Multilayer thin-film structures have been extensively studied, and numerous approaches to achieving the desired performance characteristics for a broad range of applications have been described (see, for example, Ref. 1). However, in standard one-dimensional (1D) thin-film structures, the coupling between the incidence angle and the resonance wavelength cannot be eliminated. An alternative approach using birefringent materials in a thin-film structure to achieve a dielectric mirror with reduced angular sensitivity has also been reported.[2] This technique, however, utilizes special materials that may not be compatible with standard semiconductor fabrication techniques and optical system integration. Another approach to circumventing this trade-off between field of view and signal bandwidth uses spherical interferences filters, fabricated by deposition of multilayer thin films on spherical, rather than planar, surfaces.[3] However, for this type of device to function properly, the multilayer structure must remain locally flat, and the size of the structure cannot be reduced significantly.

To achieve a wide-field-of-view wavelength-selective filter that is suitable for free-space applications and compatible with standard microfabrication techniques, we extend the concept of a resonant cavity (e.g., a Fabry–Perot resonator) into two dimensions: to achieve high mirror reflectivity for all incidence angles, we employ a photonic crystal[4]; to maintain fixed cavity-resonance conditions for all incidence angles, we need to design a resonant cavity that remains rotationally invariant. Thus, for free-space applications, we investigate a hybrid filter structure composed of a periodic array of resonant nanocavities in a 2D photonic crystal built on a planar substrate. In contrast to guided-wave 2D photonic crystal realizations[5] in which the transverse aperture size of the device is limited by the maximum achievable etch depth, the nanocavities described in this Letter are based on the three-material approach to implementing 2D photonic crystals.[6,7] This approach is advantageous in that the input aperture plane is coincident with the surface of the wafer (see Fig. 1), facilitating large-aperture devices for free-space filter applications.

A schematic diagram of such a photonic crystal with periodic defects that create a linear array of nanocavities is shown in Fig. 1. A defect, consisting of a perturbation of the refractive index of the material in the central layer of the structure, is introduced into every third period Λ of the photonic crystal. Because of the planar nature of the filter, the structure shown in Fig. 1 is not the exact 2D analog of a Fabry–Perot resonant cavity filter and thus does not exhibit complete angular insensitivity. Nevertheless, our results show that a quasi-2D resonant filter exhibits high transmissivity (greater than 0.5 for incidence angles up to approximately $\pm 30°$) and reduced angular sensitivity in the plane containing the grating vector and the substrate surface-normal vector.

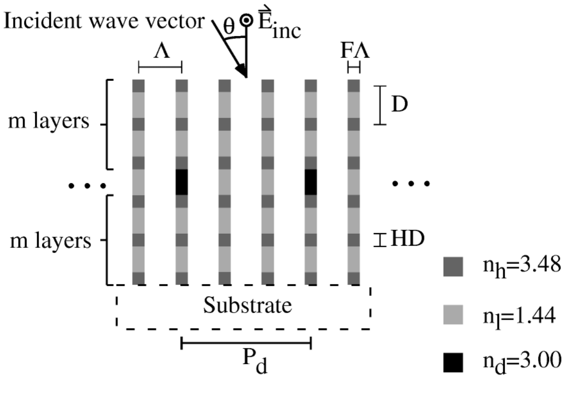

Fig. 1. Schematic diagram of the periodic array of nanocavities, where $\Lambda = 0.3394\lambda$, $F = 27.6\%$, $D = 0.3044\lambda$, $H = 32.9\%$, $m = 7$, and $P_d = 3\Lambda$.

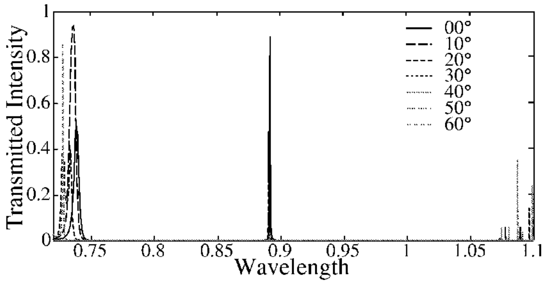

Fig. 2. Transmissivity for incidence angles ranging from $\theta = 0°$ (normal incidence) to $\theta = 60°$ as a function of wavelength for a filter structure with $P_d = 3\Lambda$, $m = 7$, and $n_d = 3.0$.

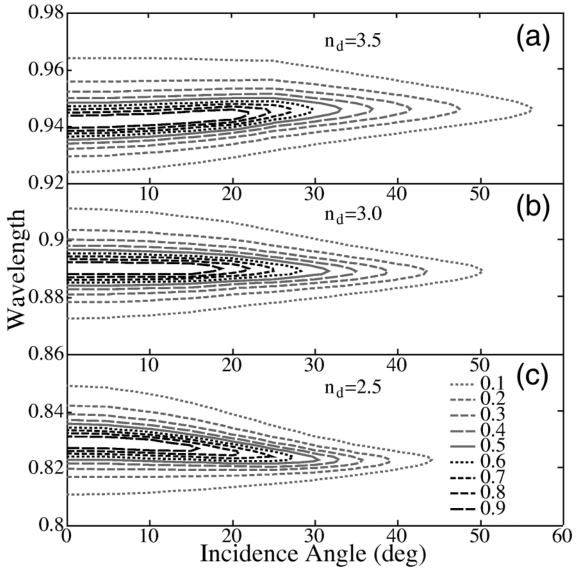

Fig. 3. Transmissivity as a function of incidence angle and wavelength for a filter structure with $P_d = 2\Lambda$, $m = 3$, and defects of refractive index (a) $n_d = 3.5$, (b) $n_d = 3.0$, and (c) $n_d = 2.5$.

Using an electromagnetic near-field analysis tool[7] based on the rigorous coupled-wave analysis method,[8] we investigate the transmissivity of the filter shown in Fig. 1 as a function of the wavelength and the incidence angle (ranging from 0° to 60°) for TE-polarized incident light, as shown in Fig. 2. Figure 2 clearly shows the existence of the photonic bandgap of the structure, from approximately $\lambda = 0.75$ to $\lambda = 1.07$ (normalized to the design wavelength of the base photonic-crystal structure described in Ref. 7), as well as a narrow transmission band centered at approximately $\lambda = 0.89$ that is due to the presence of the defects, yielding the desired performance.

In a standard Fabry–Perot resonant cavity, the optical path length inside the cavity determines the resonance wavelength. Since the cavity shown in Fig. 1 is a quasi-2D cavity, changing the geometric size of the cavity in one dimension would disrupt the angular performance of the filter. Instead, altering the refractive index of the defect material in the structure will alter the resonance wavelength of the cavity in an approximately uniform way for all incidence angles. Figure 3 shows the transmissivity of three filters similar to the structure shown in Fig. 1, with various values of material refractive index n_d in the defect. As the index of the defect increases, thereby increasing the optical thickness of the cavity, the resonance wavelength increases, as expected for a standard Fabry–Perot resonator. Since the filter structure shown in Fig. 1 is not fully rotationally isotropic about the defect sites, a change in the defect refractive index affects the resonance condition in a slightly nonuniform way for different incidence angles, as observed in Fig. 3. The resonant wavelength of the cavity can also be controlled by uniform rescaling of the nanostructure, shifting the cavity resonance and photonic crystal bandgap in tandem.

The transmissivities of three-photonic crystal microcavities composed of $m = 3$, $m = 5$, and $m = 7$ photonic-crystal layers on each side of the defect layer are shown in Figs. 4(a), 4(b), and 4(c), respectively. As in a Fabry–Perot resonator with distributed Bragg reflectors, increasing the number of reflector layers increases the Q factor of the cavity and hence decreases the passband width of the filter. Another important observation is that the width of the passband gradually tapers as the incidence angle increases (see Fig. 4). As the incidence angle increases, the effective number of photonic-crystal periods encountered by the optical wave in traversing the structure increases as well. Thus, for higher incidence angles the effective Q of the cavity increases, reducing the width of the passband.

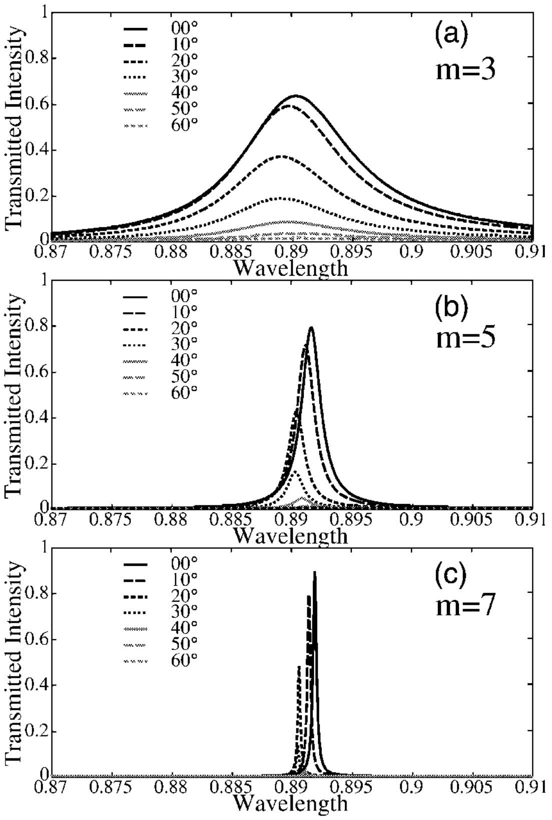

Fig. 4. Transmissivity for incidence angles ranging from $\theta = 0°$ (normal incidence) to $\theta = 60°$ as a function of wavelength for a 2D photonic crystal microcavity with $P_d = 3\Lambda$, $n_d = 3.0$, and (a) $m = 3$ (7 layers total), (b) $m = 5$ (11 layers total), and (c) $m = 7$ (15 layers total).

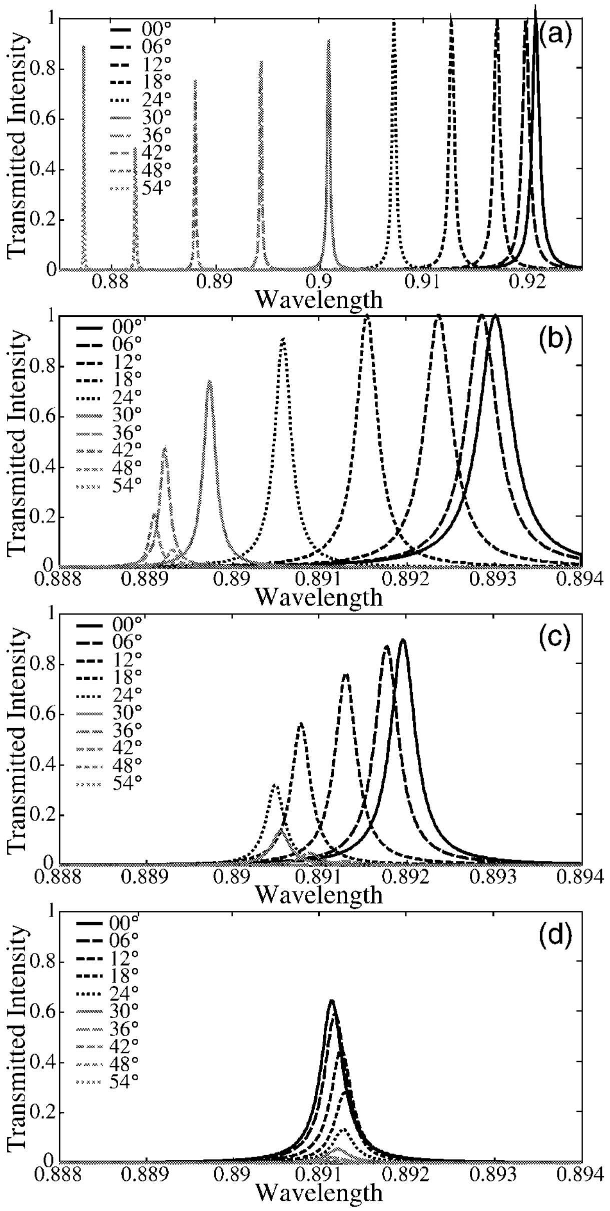

Fig. 5. Transmissivity for incidence angles ranging from $\theta = 0^\circ$ (normal incidence) to $\theta = 54^\circ$ as a function of wavelength for a 2D photonic crystal microcavity filter with $m = 7$, $n_d = 3.0$, and defect periods (a) $P_d = \Lambda$, (b) $P_d = 2\Lambda$, (c) $P_d = 3\Lambda$, and (d) $P_d = 4\Lambda$.

Finally, we compare the quasi-2D filter shown in Fig. 1 and a standard 1D Fabry–Perot filter. Figures 5(a), 5(b), 5(c), and 5(d) show the transmissivity versus wavelength for filters with $P_d = \Lambda$, $P_d = 2\Lambda$, $P_d = 3\Lambda$, and $P_d = 4\Lambda$, respectively. Note that $P_d = \Lambda$ results in a quasi-1D resonant filter, whereas $P_d = 4\Lambda$ results in a quasi-2D resonant photonic-crystal filter structure, and that, as the effective dimensionality of the resonant cavity shifts from quasi-1D to quasi-2D, the angular dependence of the filter passband gradually diminishes. In addition, the total transmissivity of the filter decreases as the defect separation increases, because of the decreasing number of defects in a given transverse area of the structure. Consequently, the optimal defect period will depend on the specific application—increasing the separation between the defects improves the angular insensitivity of the filter but at the cost of reduced total transmissivity.

We have designed and analyzed a wide-field-of-view narrow-band wavelength filter achieved by introduction of periodic material substitution defects into a 2D photonic-crystal nanostructure. The design, based on a three-material 2D photonic crystal, permits the construction of large-aperture free-space filter structures by use of standard fabrication techniques. We investigated the effect of the defect's refractive index on the resonance wavelength of the structure, and the effect of the number of photonic crystal layers on the nanocavity Q and spectral passbands, and found its behavior to be consistent with that of standard Fabry–Perot resonators. Finally, we investigated the effect of the separation of the defects on the filter performance and found that increasing the defect separation reduces the angular sensitivity of the passband while also decreasing the total transmissivity of the filter. Although this trade-off cannot be avoided in a quasi-2D filter structure, the filter performance can be optimized to best meet the needs of a specific application because of the additional design degrees of freedom of the nanostructure.

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