Single-mode waveguide microcavity for fast optical switching

Pierre R. Villeneuve, Daniel S. Abrams, Shanhui Fan, and J. D. Joannopoulos

Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received July 26, 1996

We investigate the properties of a tunable single-mode waveguide microcavity that is well suited for frequency modulation and switching. The cavity mode has a volume of less than one cubic half-wavelength, and the resonant frequency is tuned by refractive-index modulation. We suggest using a photorefractive effect to drive the device, based on the photoionization of deep donor levels known as DX centers in compound semiconductors. Picosecond on–off switching times are achievable when two of these cavities are placed in series. The resulting switch has the advantages of being compact and requiring as little as 10 pJ of energy of operate. © 1996 Optical Society of America

Photonic crystals have attracted much attention in recent years in the fabrication of high-Q microcavities. The introduction of a local defect inside a perfect three-dimensional periodic dielectric structure may give rise to a sharp resonant state inside the crystal in the vicinity of the defect. Strong field confinement can be achieved with a modal volume of less than one cubic half-wavelength. The frequency of the resonant mode is determined by the size and shape of the defect and by its refractive index.[1]

Typically, the defect is introduced during crystal fabrication by some mechanical process. Although the frequency of the mode depends on the defect's size and shape, mechanical alterations of the crystal are not practical for tuning the frequency. A preferred approach to tuning consists of changing the refractive index of the defect, because this parameter can be adjusted by external mechanisms, either optical or electronic, after the fabrication of the crystal.

The ability to tune the frequency of a resonant mode is particularly useful for the fabrication of photonic integrated devices, such as tunable filters, optical switches and gates, channel drop filters, and optical interconnects. In this Letter we present a numerical analysis for a tunable high-Q microcavity strongly coupled to the guided modes of a standard channel waveguide. We make the cavity by etching a series of holes into a channel waveguide.[2,3] We introduce a small phase shift (or defect) into the array by increasing the distance between two neighboring holes. This particular geometry easily lends itself to the design of integrated devices such as modulators.[4]

The cavity is shown in the inset of Fig. 1(a). Four holes are etched on either side of the defect, shown here in the middle of the cell. The dimensions of the cavity are chosen to achieve single-mode operation over a wide range of frequencies. The modes in the waveguide couple their energy to the resonant mode in the cavity by the evanescent field across the array of holes. We compute the transmission by using a finite-difference time-domain method. Maxwell's equations are solved in two dimensions[5] on a simple square lattice, and the derivatives are approximated at each lattice point by corresponding centered differences.[6] The computational cell is bounded by perfectly matched layers[7] with quartic absorption profiles[8] to minimize back-reflections into the cell.

We excite the fundamental mode of the waveguide at one end of the computational cell and let it propagate along the guide. The electric field is polarized in the plane. Figure 1(a) shows the transmission spectrum through the cavity normalized with respect to the incident intensity. A wide gap can be seen between frequencies $f = 0.21c/a$ and $f = 0.32c/a$, and a sharp resonant mode appears inside the gap at frequency $f_0 = 0.25c/a$. The resonance is the only mode inside the cavity over the entire range of the gap. The frequency is normalized with respect to a, where a is the distance between holes, center to center. By normalizing the frequency with respect to a, we can apply the results to any given length scale. In particular, in the case when

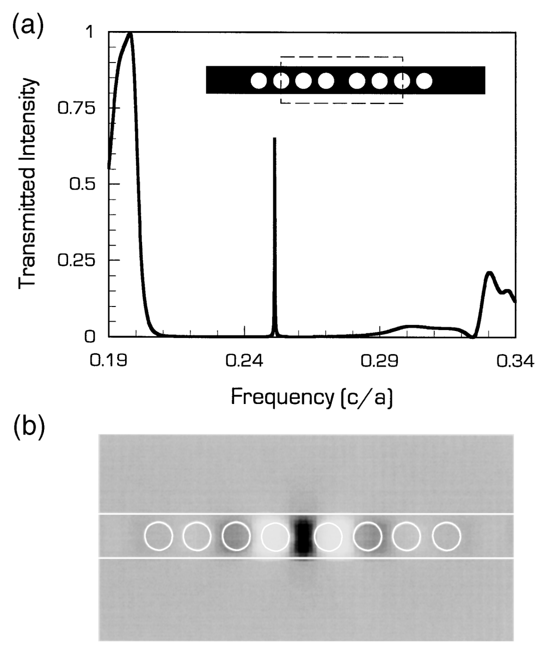

Fig. 1. (a) Transmission spectrum through the cavity normalized with respect to the incident intensity. The waveguide has a refractive index of 3.37, a width of $1.19a$, holes of radius $0.35a$, and a defect of $1.38a$, where a is the distance between holes, center to center. The cavity is single mode over the entire width of the gap. The inset shows the top view of the microcavity. (b) Magnetic field distribution of the resonant mode. The magnetic field is polarized in the normal direction; black (white) corresponds to a field pointing up (down). Gray corresponds to zero field. The overlay indicates the position of the microcavity.

0146-9592/96/242017-03$10.00/0

the cavity is operated at a wavelength of 1.55 μm the waveguide region outlined in Fig. 1(a) covers an area of 1 μm^2.

The field pattern of the resonant mode is shown in Fig. 1(b). The mode is strongly confined in the vicinity of the defect and decays exponentially across the array of holes. In addition, the mode is strongly confined along the transverse direction by the high-index waveguide. The mode has even symmetry with respect to the plane running through the middle of the waveguide. Hence it is not surprising that the fundamental mode of the waveguide—which also has even symmetry—couples efficiently into the cavity. The two modes have a large overlap.

The transmission at resonance is 65% of the incident intensity. The quality factor Q of the cavity—which is a measure of the total losses—is given by $f_0/\Delta f$, where f_0 is the resonant frequency and Δf is the full width at half-maximum of the resonator's Lorentzian response. In this case the Q factor is 1300.

We can tune the frequency of the resonant mode by changing the refractive index of the dielectric material. Inasmuch as the mode is strongly confined in the vicinity of the defect—its volume is less than one cubic half-wavelength—only a small area of the cavity needs to be affected to shift the resonance. If we assume that a fraction σ of the mode is located inside the dielectric material contained within the dashed box in Fig. 1(a), the frequency shift δf of the resonance will be given by

$$\delta f = \left(\frac{1}{1 + \frac{\sigma \delta n}{n}} - 1 \right) f_0 \qquad (1)$$

for small changes of the index $\delta n/n$. The mode shown in Fig. 1(b) has roughly 80% of its electrical energy density inside the dielectric material. Figure 2 shows a plot of Eq. (1) for the case when $\sigma = 0.80$. We see that the frequency modulation is essentially linear over the entire range of $\delta n/n$. To resolve two peaks, the index variation will need to be sufficiently large to shift the resonance by at least one width, i.e., $\delta f > \Delta f$. This inequality sets a lower limit on the index variation required if the device is to be operated as a switch. Using Eq. (1) along with the definition for Q, we can write an expression for the minimum index change required for switching:

$$\left| \frac{\delta n}{n} \right|_{\min} = \frac{1}{\sigma} \frac{1}{Q \pm 1} \approx \frac{1}{\sigma Q}, \qquad (2)$$

where the fast part of the expression is valid for large values of Q. The + (−) in the denominator corresponds to a negative (positive) index change.

For this cavity the magnitude of the minimum index variation is 1×10^{-3}, as computed from expression (2). We introduce a variation of -3×10^{-3} (for reasons to be discussed presently) and investigate the transmission. The index variation is generated only inside the dielectric material outlined by the dashed box in Fig. 1(a). The spectrum of the transmitted pulse is shown in Fig. 3 along with the spectrum of the original pulse. The resonant frequency is shifted upward because the index variation is negative. The two curves in Fig. 3 are clearly resolved.

Many different mechanisms can be used to change the refractive index inside the cavity. The most common ones include the electro-optic effect and the charge-carrier effect. However, both of these mechanisms result in small index changes, typically less than 10^{-3}. In this Letter we propose a different approach that holds great promise for the generation of large index variations, a photorefractive effect based on the ionization of deep donor levels known as DX centers. Large index variations can be optically induced in certain compound semiconductors with index changes 30 times larger than that of conventional photorefractive materials.[9] The index variations occur from the capture of electrons by DX centers. In the DX state two electrons are trapped by a positively charged donor and produce a negatively charged ion. Thermal excitation out of the traps is limited by an energy barrier, whose height determines the lifetime of the DX centers. Inasmuch as each absorbed photon creates a pair of carriers, the index change increases linearly with the local illumination intensity. This photorefractive effect has been shown to give rise to index changes $\delta n/n$ as large as -3×10^{-3} in Si-doped $Al_{0.27}Ga_{0.73}As$ samples at $\lambda = 633$ nm.[9]

The on–off switching speed of the cavity is determined by the time required for ionization of the DX centers and by the time that the electrons take to

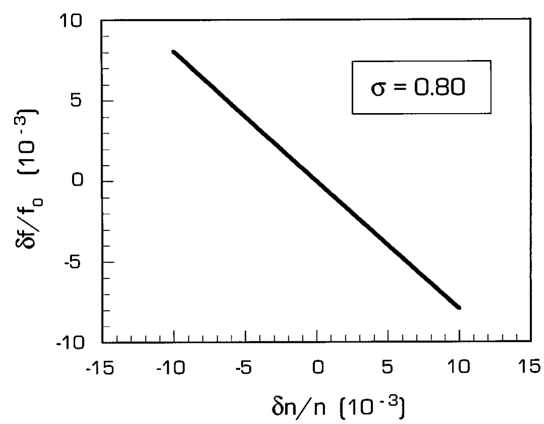

Fig. 2. Resonant frequency shift as a function of index change in the cavity, computed from expression (2).

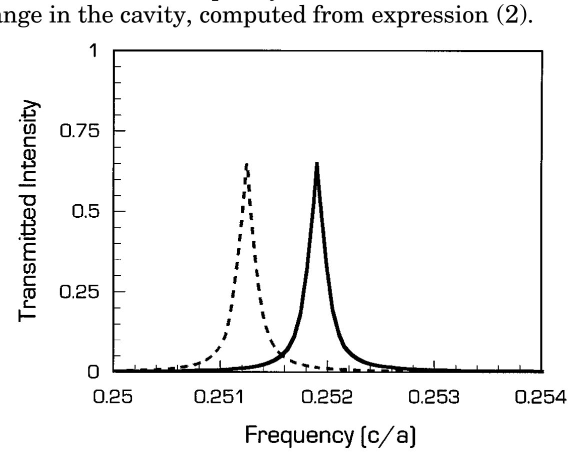

Fig. 3. Transmission spectrum through the index-modulated cavity (solid curve) with an index change of -3×10^{-3}. The spectrum of the unshifted resonance is also shown (dashed curve).

decay out of the traps. Various sources, such as mode-locked diode lasers with wavelengths ranging from 0.6 to 1.6 μm, can be used to ionize the DX centers. The ionization time (switch-on time) is determined by the rise time of the source and can be as small as 1 ps.

The decay time of the DX centers (switch-off time) is a function of temperature. At room temperature, electrons may take as much as 1 ns before overcoming the energy barrier.[10] Such a long decay time severely limits the on–off switching speed. To overcome this limitation we suggest using a different approach, one that is inspired by techniques used for the generation of ultrashort laser pulses[11] and fast switching in Mach–Zehnder-type geometries[12] when slow nonlinear processes are involved. This configuration is presented only for illustrative purposes; it allows us to introduce some of the real issues that potential users will need to address.

Our approach consists in using two cavities in series, one to trigger the switch on and the other to trigger it off. The two cavities are designed such that the resonant frequency of the first cavity is centered at $f_0 - \delta f$ and that of the second cavity is centered at f_0. Because the cavities are tuned to different frequencies, light cannot pass through the switch. We can turn the switch on—in as little as 1 ps—by triggering the first cavity such that its resonance moves to f_0, matching that of the second cavity. We can turn the switch off—again in 1 ps—by triggering the second cavity to a frequency $f_0 + \delta f$. This scheme would allow the switch to be turned on and off in a total of 2 ps.

Although the switch can be turned on and off very quickly, the switch requires as much as 1 ns to recover before it can be triggered again. During this time the electrons thermally overcome the capture barrier, and the resonance frequency of each cavity shifts back to its initial position. The recovery time is determined by the height of the energy barrier.[13] During the recovery time there is minimal leakage through the switch because the two cavities relax at the same rate and therefore remain detuned with respect to each other during the entire recovery period.

The energy required for operating the switch is determined by the doping concentration and the photon absorption efficiency inside the semiconductor and by the surface area of the microcavity. In the case of Si-doped $Al_{0.27}Ga_{0.73}As$ with a doping concentration of 4×10^{18} cm^{-3} and a photon absorption efficiency of 0.1%, a fluence of 1 mJ cm^{-2} generates an index variation larger than -3×10^{-3}.[9] As the microcavity has a surface area of roughly 1 μm^2, only 10 pJ of energy is required for operation of the switch. We could reduce the energy requirement even further either by increasing the doping concentration or by increasing the absorption efficiency.

Turning the switch on and off in less than 10 ps will require a driving laser pulse duration on the same time scale and hence a minimum peak power of 1 W. This kind of power can readily be obtained with current state-of-the-art diode lasers. Furthermore, only 0.1% of the injected power will get absorbed by the switch, leaving 1 mW of power to be dissipated between events. If we intend to operate the switch at even greater speeds, we will need to reduce the quality factor Q of the cavity. Indeed, when $Q = 1300$ the photon lifetime inside the cavity is close to 1 ps (if $\lambda = 1.55$ μm), which sets a limit on the switching speed. By reducing the cavity Q we will be able to reduce the photon lifetime, but this will also have the effect of broadening the resonance, which in turn will lead to a higher energy requirement for the generation of a sufficiently large frequency shift.

In summary, we present the design of a single-mode tunable microcavity that can be used for frequency modulation and switching. We can achieve fast on–off switching by placing two of these cavities in series. Because a large fraction of its surface is exposed, the switch is well suited to being driven optically. We propose to drive the switch by using a photorefractive effect based on the photoionization of DX centers. The switch's small size ($<$10 μm in length) and small turn-on–turn-off energy ($\simeq$10 pJ) are ideal for large-scale integration in photonic integrated circuits.

The authors acknowledge helpful discussions with Richard Linke, Piotr Belca, and Erich Ippen. We thank Jerry Chen for the use of his two-dimensional code with quartic absorption boundary conditions. This study was supported in part by the Materials Research Science and Engineering Center program of the National Science Foundation under award DMR-9400334. D. S. Abrams gratefully acknowledges support from a National Defense Science and Engineering Graduate fellowship.

References

1. J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals* (Princeton U. Press, Princeton, N.J., 1995), Chaps. 5 and 6.
2. P. R. Villeneuve, S. Fan, J. D. Joannopoulos, K. Y. Lim, G. S. Petrich, L. A. Kolodziejski, and R. Reif, Appl. Phys. Lett. **67,** 167 (1995).
3. S. Fan, J. N. Winn, A. Devenyi, J. C. Chen, R. D. Meade, and J. D. Joannopoulos, J. Opt. Soc. Am. B **12,** 1267 (1995).
4. M. Y. Liu and S. Y. Chou, Appl. Phys. Lett. **68,** 170 (1996).
5. We have tested our results with a similar time-domain code in three dimensions. The two-dimensional code has consistantly proved to be reliable for the analysis of these microcavities.
6. K. S. Yee, IEEE Trans. Antennas Propag. **AP-14,** 302 (1966).
7. J. P. Berenger, J. Comput. Phys. **114,** 185 (1994).
8. J. C. Chen and K. Li, Microwave Opt. Technol. Lett. **10,** 319 (1995).
9. R. A. Linke, T. Thio, J. D. Chadi, and G. E. Devlin, Appl. Phys. Lett. **65,** 16 (1994).
10. R. A. Linke, NEC Research Institute, Inc., Princeton, N.J. 08540 (personal communication).
11. E. Ippen, Appl. Phys. B **58,** 159 (1994).
12. S. Nakamura, K. Tajima, and Y. Sugimoto, Appl. Phys. Lett. **67,** 2445 (1995).
13. It may be possible to reduce the recovery time by raising the temperature or by changing the chemical composition of the semiconductor.