Air-bridge microcavities

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We introduce and analyze a new type of high-Q microcavity consisting of a channel waveguide and a one-dimensional photonic crystal. A band gap for the guided modes is opened and a sharp resonant state is created by adding a single defect in the periodic system. An analysis of the eigenstates shows that strong field confinement of the defect state can be achieved with a modal volume less than half of a cubic half-wavelength. We also present a feasibility study for the fabrication of suspended structures with micron-sized features using semiconductor materials. © *1995 American Institute of Physics.*

Boundary conditions can strongly affect atomic radiative dynamics. For instance, electromagnetic cavities with perfectly reflecting walls have the ability of altering the density of allowed states for radiative transitions. By scaling down the dimensions of the cavity to the atomic transition wavelength, the density of states becomes spectrally discrete, and atomic radiative decay can be either enhanced or suppressed, depending on whether or not the transition frequency coincides with the resonance.

Electromagnetic cavities have been fabricated at microwave frequencies using metallic walls. However, at optical frequencies, metals become very lossy and one needs to turn to other materials. In recent years, low-loss dielectric materials have been used for the fabrication of optical microcavities; several approaches have been used, such as total internal reflection in microdisks and one-dimensional Fabry–Perot resonators.[1] It has also been suggested that ''photonic crystals'' could be used for the fabrication of optical microcavities since they are made of low-loss dielectric materials and reflect light in all 4π steradians for a large range of frequencies.[2,3]

In this letter, we introduce a novel class of coplanar microcavities which uses index guiding to confine light along two dimensions and a one-dimensional photonic crystal to confine light along the third. Conceptually, this approach is analogous to that used in one-dimensional Fabry–Perot resonators, but it differs in that it has both a coplanar geometry and the ability to give rise to strong field confinement. The microcavities are made of high-index channel waveguides in which a strong periodic variation of the refractive index is added along the axial direction. The periodic index is introduced by vertically etching a series of holes through the guide. The guided modes undergo multiple scattering by the periodic array of holes causing a gap to open between the first and second guided-mode bands. The size of the gap is determined by the dielectric constant of the waveguide and by the size of the holes.

By introducing a defect in the periodic array of holes, a sharp resonant mode can be introduced within the gap. If the defect consists of extra dielectric material between two of the holes, then a defect state is ''pulled down'' from one of the above guided-mode bands. The state appears initially at the top of the gap and is pulled deeply into the gap by increasing the size of the defect. Since this defect state can be expanded primarily in terms of the guided modes, its projection onto the continuum is very small. This leads to a resonant mode which is highly confined within the vicinity of the defect. It can only couple its energy to the waveguide mode through the evanescent fields across the array of holes.

In order to achieve good confinement of the radiation in the microcavity, it is essential that the index contrast between the waveguide and the substrate be as large as possible to keep the mode from extending significantly into the substrate. Although it is possible for the radiation to be well confined if the cavity is placed directly on a low-index substrate,[4] maximum confinement can be reached by completely surrounding the cavity with air. This can be done by removing part of the substrate from under the microcavity as shown in Fig. 1. We have chosen to show, in this specific case, a microcavity with three holes on either side. Two of these holes are in the suspended section of the guide while the other hole extends into the substrate. By etching the third hole deeply below the surface of the substrate, we can optimize the backscattering of the guided modes which extend under the waveguide. The total number of holes can be adjusted in order to change the reflectivity on either side of the cavity. By increasing the number of holes in the structure,

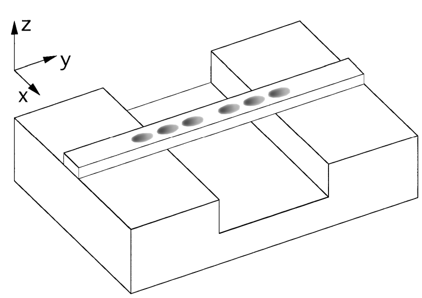

FIG. 1. Suspended coplanar microcavity. The distance from center to center between neighboring holes is the lattice constant a. The diameter of the holes is $0.6a$ and the width and height of the guide are $1.2a$ and $0.4a$, respectively.

field confinement can be increased at the expense of our ability to couple light in and out of the microcavity. A good compromise can be reached by reducing the number of holes on only one side of the cavity.

To model these devices, we have used the supercell approximation. In this method, a bridge structure is placed into a large supercell and is repeated periodically in space. Using Bloch's theorem, Maxwell's equations are expanded in a plane-wave basis and transformed into a matrix eigenvalue problem, which is solved with standard numerical techniques. The details of our computational method can be found elsewhere.[5] We chose a supercell made of the structure shown in Fig. 1 and its mirror image in the *xy*-plane at the bottom of the substrate in order for the supercell to have inversion symmetry. By choosing the substrate sufficiently large, the interaction between the two microcavities can be made small; in all our calculations, we have chosen the thickness of the substrate such that the splitting between the eigenvalues converged to within 0.5%. The size of the supercell was chosen to include three holes on either side of the microcavity and the total thickness of the substrate was chosen to be equal to $4a$, where a is the distance from center to center between neighboring holes.

The microcavity material was chosen to be GaAs with a refractive index of 3.37 at 1.55 μm[6] and the substrate was chosen to be $Al_{0.3}Ga_{0.7}As$ with a refractive index of 3.07 also at 1.55 μm.[6] The small index contrast between these materials would not allow for strong confinement of the guided modes if the cavity was placed directly on top of the substrate. However, we have chosen these materials to demonstrate that a suspended structure can allow for strong field confinement within a distance as little as $2a$ on either side of the defect and radiation losses into the substrate can be negligible in spite of the small index contrast.

The different parameters of the microcavity are the width and height of the waveguide, the radius of the holes, the distance between neighboring holes, the number of holes on each side of the cavity, and the size of the defect. Since the microcavity can be scaled to any wavelength simply by scaling every parameter, it is convenient to choose one parameter and scale the other with respect to it. In this letter, we have chosen to scale every parameter with respect to a.

By changing the different parameters, we can adjust the number of resonant modes in the gap, the frequency of these modes, and their confinement in the cavity. In the specific case shown in Fig. 1, a gap opens up between the first and second guided-mode bands from $f_0 = 0.282c/a$ to $f_0 = 0.371c/a$, where f_0 is the free-space frequency, and c is the speed of light in vacuum. A local defect of size $d = 1.5a$ introduces a single resonant mode in the gap at $f_0 = 0.313c/a$ where d is the distance from center to center between the holes on either side of the defect. A defect size of $1.5a$ corresponds to a quarter-wave phase shift and yields the strongest field confinement of the resonator mode. Unlike Fabry–Perot resonators, the quarter-wave phase shift in the microcavity does not introduce a mode in the middle of the gap. Instead, the mode appears about a third of the way up from the bottom of the gap. The electric and magnetic fields of the resonator mode are shown in Fig. 2. The electric field is polarized mostly in the plane of the substrate while the magnetic field is mostly normal to the substrate. The electric field has a nodal point at the center of the cavity. The fields decay rapidly; the modal volume is smaller than half of a cubic half-wavelength.

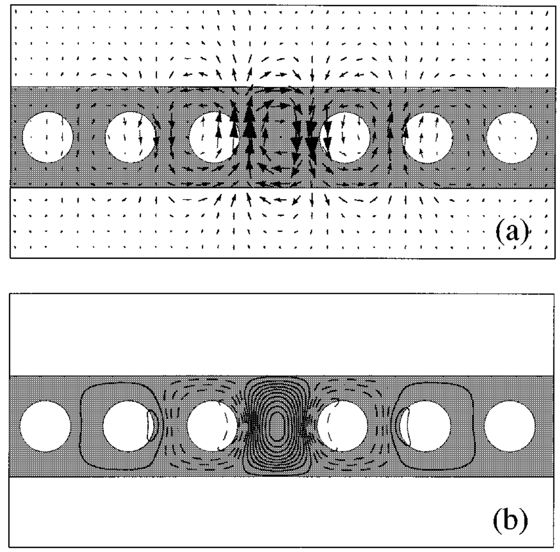

FIG. 2. (a) Vector plot of the electric field in the plane of the substrate, (b) contour plot of the normal component of the magnetic field. In both cases, the fields are shown on a plane passing through the center of the guide. The dielectric structure is shown in gray.

To couple light from the waveguide into the defect state, the waveguide mode must have a component of the same symmetry as that of the defect state. Since TE modes[7] have the same symmetry with respect to the *xy*-plane, they are more likely to couple energy efficiently into the cavity mode.

To estimate the quality factor (Q-factor) of this cavity mode, we performed a time-dependent analysis in two dimensions. The structure was reduced to an infinitely tall waveguide with long holes. We introduced an initial pulse into the microcavity and computed the number of optical cycles required for the power to decay by a factor of $e^{-2\pi}$. A more detailed description of this procedure can be found elsewhere.[8] We found a Q-factor greater than 10^4 for a structure with seven holes on either side of the defect. Moreover, Kurland *et al.*[9] have recently performed a similar two-dimensional time-dependent analysis to estimate the effect of random disorder at the dielectric-air interfaces. Their calculations showed that deviations arising during the fabrication process should not affect the Q-factor significantly; they found a Q-factor greater than 8000 in a structure with surface disorder as large as 20% of the width of the waveguide.

The mode shown in Fig. 2 is the lowest-order resonator mode. Since the introduction of the defect may cause several states to be "pulled down" from the upper bands, more than one state could potentially appear in the gap. In the structure presented above, the first higher-order defect state appears at a frequency of $0.373c/a$ which is aligned with the second band, outside of the gap. Although they are aligned, the defect state and the guided modes of the second band do not couple with each other since they do not have the same symmetry. Indeed, the first higher-order mode has the symmetry

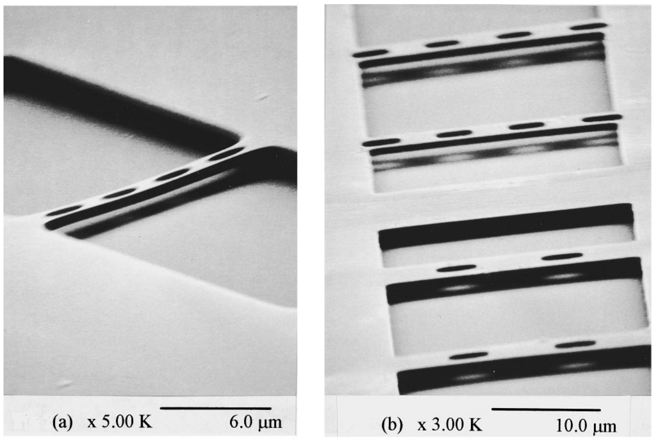

FIG. 3. (a) SEM micrograph of the Si bridge. The bridge has a length of 10 μm and a width of 4 μm. The holes are 2 μm in diameter and are separated by 3 μm from center to center. (b) SEM micrograph of GaAs bridges. The bridges are 20 μm in length and range from 3.5 to 5.5 μm in width. The holes are all 2.5 μm in diameter and are separated from center to center by 7.5 μm (foreground) and 5 μm (background).

of the third band. The mode remains well confined around the defect. The large separation between the fundamental mode and the higher-order modes ($\Delta f/f_0 > 19\%$) will allow these microcavities to be operated with a single-mode output.

We have begun exploring the possibilities of fabricating these microcavities with silicon-based materials and with III–V semiconductor-based materials. Our main objective is to demonstrate the feasibility of building suspended structures with micron-sized features.

In the silicon-based system, a 1.0 μm thick layer of sacrificial SiO_2 was deposited by low-temperature chemical vapor deposition onto a Si substrate. A 0.5 μm thick layer of amorphous Si was deposited on top of the oxide by low-pressure chemical vapor deposition. The bridge pattern was defined using photolithography and the two deposited layers were then anisotropically removed by reactive ion etching. Finally, the sacrificial oxide was selectively etched away with dilute hydrofluoric acid. A micrograph of the bridge structure imaged with a scanning electron microscope (SEM) is shown in Fig. 3(a). The Si bridge is 10 μm long and 4 μm wide. Four holes with a diameter of 2 μm are placed periodically along the bridge and are separated by 3 μm, center to center.

In the case of the III–V semiconductor materials, a 1.0 μm thick layer of sacrificial AlAs and a 0.5 μm thick layer of GaAs were grown sequentially by gas source molecular beam epitaxy on a GaAs substrate. The bridge pattern was again defined using photolithography and the two layers were anisotropically removed by reactive ion etching. The sacrificial material was then selectively etched away by a chemical etch. Figure 3(b) shows a SEM micrograph of a series of GaAs bridges. These bridges are 20 μm in length and range from 3.5 to 5.5 μm in width. The holes are all 2.5 μm in diameter and are separated by 7.5 μm from center to center in the structures shown in the foreground, and 5 μm for those in the background. The successful fabrication of these suspended structures constitutes a major step in the realization of the ultimate device. Optical measurements are beyond the scope of this work and will be performed in future experiments.

We have presented and analyzed a new class of resonant microcavities integrated directly along the plane of the substrate, and have demonstrated that they are amenable to fabrication. We found that these microcavities give rise to strong field confinement and allow for efficient coupling into channel waveguides. By concentrating the field fluctuations into a small volume, we expect that the recombination rate of carriers will be increased. This could lead to the enhancement of spontaneous emission and could allow the microcavities to be modulated at very high speeds. These new microcavities offer exciting possibilities for the fabrication of high density and high speed optical interconnects and ultralow threshold microlasers.

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