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Transverse modes of photonic crystal vertical-cavity lasers

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The control of lateral mode operation using a photonic crystal in a vertical-cavity surface-emitting laser (VCSEL) is analyzed and confirmed experimentally. By controlling design parameters of the photonic crystal pattern, we have produced photonic crystal VCSELs that operate in higher order defect modes in addition to the fundamental defect mode. The transverse modal behavior is consistent with the predictions of a theoretical model in which the etching depth dependence of the air holes of the photonic crystals is considered. We also have determined the lower limit of optical confinement required from the photonic crystal pattern to influence the output beam of the laser. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1646729]

Photonic crystals incorporated into vertical-cavity surface-emitting lasers (VCSELs) are useful for modal control.[1–4] Single transverse mode operation in the lowest order mode is critical in high performance optical communication systems, and high power output is also a desirable feature in a device. Because one of the properties of photonic crystals is to enlarge the optical emission area of a device while maintaining the single mode operation regime, photonic crystal VCSELs have the potential to improve single mode VCSEL manufacture. Two-dimensional photonic crystal patterns etched into the top distributed Bragg reflectors (DBRs) of VCSELs have recently been demonstrated experimentally as a method of achieving single mode operation.[1,2,4] Theoretical models (which include the effects of finite etching depth of the photonic crystal holes) have also shown that the design space in photonic crystal VCSELs allows a large variation of parameters that produce single mode operation. In addition, these models clearly delineate the design space where single mode operation and multimode operation regimes should be possible.[4] However, until now an experimental investigation into the accuracy of the theoretical models has not been carried out near the single mode operation cutoff point. In this letter, we describe the design and fabrication of devices that operate in both single mode and multimode regimes and compare their operating points with those predicted by a theoretical model. We also investigate weak confinement to determine the practical limitation of photonic crystal confinement.

The refractive index profile produced in photonic crystal VCSELs that permits single (fundamental) mode operation is similar to the situation in photonic crystal fibers.[5] A large single mode emission area can be achieved because of the strong wavelength dependence of the refractive index in the structure. Specifically, etching air holes into the top DBR of a VCSEL produces a controlled cavity resonance wavelength shift compared to the unpatterned case. As Hadley pointed out, cavity resonance wavelength shifts correspond to changes in effective index.[6] Thus, the resonance shift introduced by photonic crystals can be modeled as a small effective index reduction in the region outside a central defect in a VCSEL. The central defect, which usually consists of one, seven, or nineteen missing holes in the center of the photonic crystal pattern, forms the hexagonal lasing area of the VCSEL which is approximated as circular in the theoretical model used. The index changes are dependent on wavelength due to the properties of photonic crystals and are much smaller in magnitude than what would be expected if simply considering the air filling factor that the holes introduce into the device. That is, an average index theoretical method cannot accurately estimate the cavity resonance shift introduced by the etched array of holes. Previous experiments have verified the accuracy of theoretical models predicting the magnitude of resonance shifts, the models having included photonic crystal effects (through band diagram analysis of out-of-plane modes)[7] as well as the effects of finite etching depth.[3] The equivalent change in index of the area outside the defect permits operation in either a single fundamental photonic crystal defect mode that has an approximately Gaussian profile, or multiple transverse defect modes, depending on the design.

Ultimately, the propagating modal characteristics of the VCSEL are determined principally by the design parameters of the photonic crystal lattice. These parameters include the hole diameter, lattice constant, number of holes missing from the defect region, and etching depth. The interplay between the parameters determining single fundamental mode operation is quantified by use of the V_{eff} parameter, or normalized frequency, which is given by

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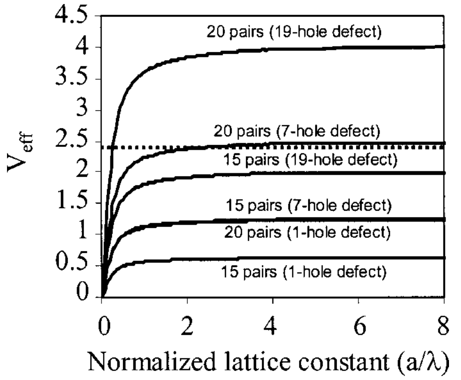

FIG. 1. Theoretical modal properties for two different etch depths and three different central defect diameters for the case where the hole diameter is half the lattice constant (a). Etch depth is measured in periods, or pairs, of the top DBR. The single mode cutoff condition is indicated by the dotted line.

$$V_{\mathrm{eff}}=\frac{2\pi r}{\lambda}\sqrt{n_m^2-n_{\mathrm{eq}}^2}, \tag{1}$$

where n_{eq} is the equivalent refractive index of the photonic crystal region surrounding the central defect (determined from band diagram analysis and etching depth dependence), n_m is the unmodified index of the defect region, r is the radius of the central defect region (which depends on the lattice constant and number of missing etched holes), and λ is the free-space wavelength.[4,5] If V_{eff} is less than 2.405, the structure is considered to be single mode.

In general, an increase in hole diameter with a given lattice constant, an increase in etching depth or an increase in the size of the central defect (by removing extra etched holes) will increase the likelihood of laser operation in multiple higher order transverse modes, rather than the lowest order single transverse mode operating point. Since n_{eq} is a decreasing function of hole diameter and depth, the mode will become unconfined by the photonic crystal defect as hole diameter and depth approach zero (n_{eq} approaches n_m). Figure 1 shows theoretical results for three different photonic crystal patterns etched into our VCSEL structure (described in the following). It is clear from Fig. 1 that increasing either the etching depth or the number of holes missing from the central region will raise the V_{eff} parameter. To obtain stable single fundamental mode operation, V_{eff} should be less than 2.405 but not so low that any external perturbations, such as carrier injected thermal effects, will overwhelm the photonic crystal induced confinement. Therefore, although the theory predicts multiple higher-order mode operation for values greater than 2.405 and single mode operation for all lower values, we expect instability from structures with weak confinement corresponding to sufficiently small V_{eff} values.

The photonic crystal design we consider consists of a triangular array of circular air holes that have been etched into the top distributed Bragg reflector of a VCSEL with an operating wavelength close to 850 nm. The VCSEL structure has $Al_{0.9}Ga_{0.1}As/Al_{0.2}Ga_{0.8}As$ DBRs surrounding the active region. The top DBR is n-type to exploit improved carrier mobility in the region of etched holes and consists of 25 mirror periods; the bottom DBR consists of 35.5 periods. For all cases examined, the photonic crystals did not penetrate into the active region. Photonic crystals were patterned with focused-ion beam etching into a SiO_2 mask layer and subsequently etched with inductively coupled plasma etching into previously characterized selectively oxidized VCSELs. The oxide aperture, needed for current confinement in these tests, was pulled back at least three photonic crystal lattice periods from the central defect region (such that the oxide aperture is large compared to the defect area) to isolate the photonic crystal-induced index changes of interest from those of the oxidized layer.

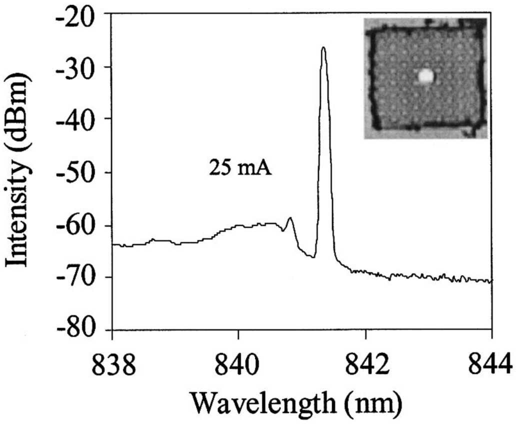

FIG. 2. Spectrum and near field image of a single-hole defect photonic crystal VCSEL operating in the fundamental mode (with lattice constant of 3.6 μm, hole diameter of 2.6 μm, and etch depth of 20 DBR periods). Single mode operation was observed at the highest currents tested.

A variety of photonic crystal structures were fabricated with optical aperture sizes (central defect diameters) less than 10 μm in diameter. Central defects consisted of single-hole, 7-hole, and 19-hole defect structures. Increasing the number of missing holes in the defect as well as deeper etches were used to increase V_{eff}. Figures 2 and 3 show fabricated VCSELs operating in the fundamental photonic crystal defect mode and in a multimode regime, respectively, under dc bias conditions. Figure 2 shows a single-hole defect device operating under single mode conditions with over 30 dB side mode suppression, and Fig. 3 shows an example of a 19-hole defect structure in photonic crystal multimode operation. The modal characteristics observed in all tested devices are summarized in Fig. 4. Of the four devices which operated under multiple higher-order mode conditions, three were 19-hole defect structures and one was a 7-hole defect structure.

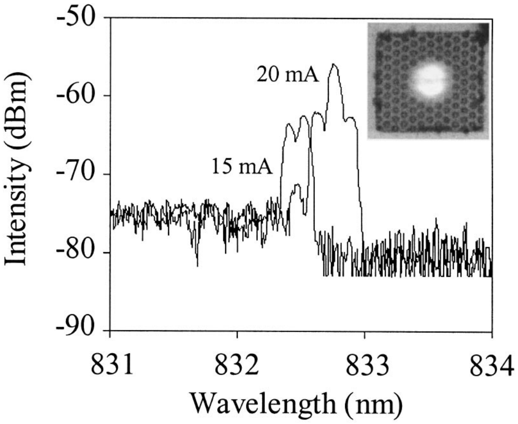

FIG. 3. Spectrum and near field image of a 19-hole defect photonic crystal VCSEL in multimode operation at two currents (with lattice constant of 3 μm, hole diameter of 1.8 μm, and etch depth of 17 DBR periods).

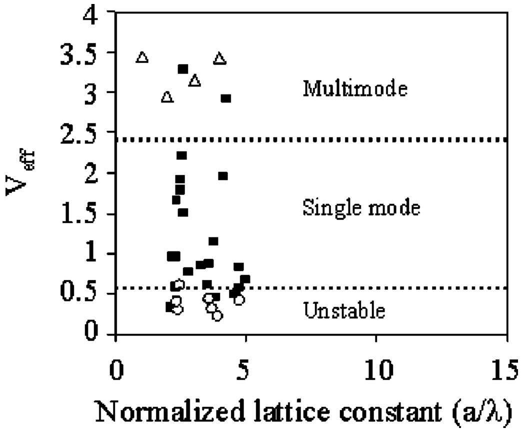

FIG. 4. Experimental results of modal properties of fabricated photonic crystal (PhC) VCSELs. Circles, squares, and triangles indicate devices operating in oxide modes, single PhC mode, and multiple PhC modes, respectively.

All had V_{eff} values greater than the cutoff condition for single mode operation, but their optical aperture diameters were not all the largest in the data set. No single-hole defect structures were found to operate in multiple lateral modes, in agreement with their calculated V_{eff} values that lie within the single mode regime. These results show that the theoretical model can be used to accurately design single mode or multimode devices for the range of aperture sizes tested.

For devices with weak confinement, we observed that the devices sometimes lased in oxide-confined modes (photonic crystal confinement was not achieved). This was easily identified because lasing occurred outside the central defect regions in these cases. These devices occupy the ‘‘unstable’’ region of Fig. 4 and indicate empirically that V_{eff} must be greater than approximately 0.6 for stable operation in the fundamental mode. We assume that with increasing aperture sizes the correspondingly lower effective index values needed for single mode operation will cause greater instability and hence break down the theoretical model, but a trend has not yet been observed from the devices tested here. In order to test devices with larger defect sizes (that is, optical apertures), larger areas of current confinement would be needed to maintain isolation of the optical aperture from the current aperture for test purposes, unless another method of current confinement is available.

In summary, we have investigated experimentally the design of single mode and multimode photonic crystal VCSELs. Good agreement was reached between a theoretical model and the data obtained experimentally. We investigated how weak the confinement from the photonic crystals can be allowed before instability results. Stable single mode operation in the fundamental mode has also been demonstrated for devices with optical apertures of up to 10 μm in diameter.

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