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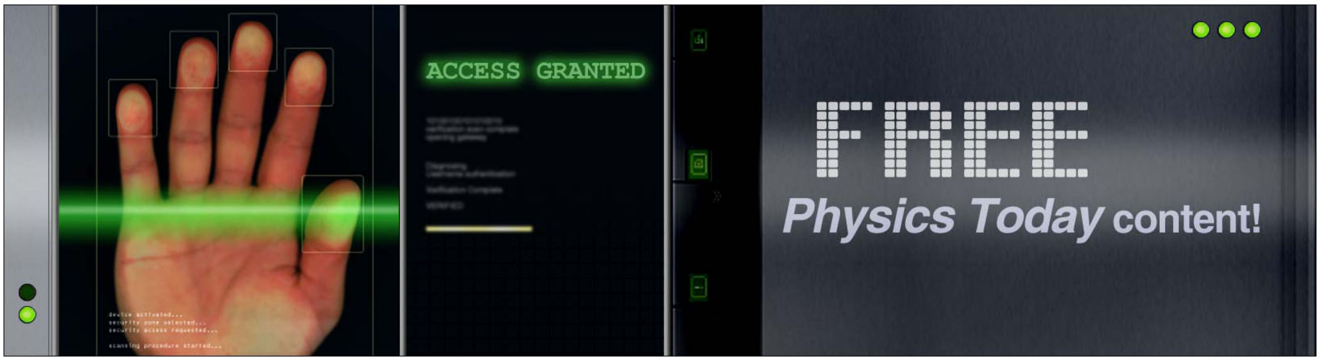

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Photonic crystal microdisk lasers

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A photonic crystal (PC) microdisk laser cavity was introduced and demonstrated. The microlaser utilizes lossless surface modes within the PC forbidden band for vertical confinement and whispering gallery modes for lateral confinement. Analysis showed that this type of cavity mode has a smaller mode volume and a larger confinement factor than other resonant modes in the microdisk stacks. Initial experiments demonstrated lasing of optically pumped wavelength-size microdisks with four period GaAs/AlGaAs PCs and InGaAs quantum dots as gain media. © *2011 American Institute of Physics*. [doi:10.1063/1.3567944]

Microlasers are important elements for integrated photonic circuits.[1] For this purpose, it is highly desirable to scale down the optical cavities in all three dimensions. The performances of microlasers highly relate to Q factor and mode volume of the laser cavity. Cavity modes with a high Q factor and a small mode volume lead to a large Purcell factor and a low threshold modal gain for lasing.[2] Microdisk and photonic crystal (PC) cavities were investigated for subwavelength semiconductor lasers as the cavity modes have relatively high Q factor among all micron size cavities.[3–5] In a microcylinder (e.g., a very thick microdisk), the mode area of whispering gallery mode (WGM) in the lateral plane reduces linearly with the microdisk diameter.[6] However, the mode size of air-cladded waveguide mode in the transverse dimension does not scale linearly with the disk thickness and has a lower bound set by the scale of wavelength. One strategy to reduce the mode size in the transverse dimension is to introduce metallic coating on microdisk supporting surface mode at the metal-dielectric interface commonly known as surface plasmon polariton (SPP) mode.[7,8] Such surface mode is tightly bound to the metal-dielectric interface with decay lengths much smaller than the wavelength. The small mode size of SPP mode leads to the small mode volume of the SPP-guided WGM. However, the loss introduced by metal sets an upper bound for the achievable Q factor of any SPP-guided modes including SPP-guided WGM. The achievable cavity Q factor is below 300 at any wavelengths below 1.5 μm, which demands significant gain or pumping to lase. To produce surface wave, the most commonly used medium with negative real part of dielectric constant ε is metal, but the nonzero imaginary part of ε leads to metal absorption loss. In view of this, it is very attractive to consider PC structures made of dielectric materials, which can provide an equivalent ε purely negative inside the forbidden band.[9] This means that surface modes can also be supported at the interface of a dielectric PC and a uniform dielectric medium. More importantly, the propagation loss of such surface mode can be zero with the zero imaginary part of the effective ε, which leads to very sharp angular reflectivity resonances in experiments on prism-coupled excitation of surface waves in one-dimensional (1D) PC.[10] The lossless propagation of surface mode in dielectric PCs offers the unique advantages for laser application over the SPP on metal surfaces. To create a small mode volume cavity with high Q factor, we designed stacked bilayers forming 1D PC along the transverse (i.e., vertical) dimension of microdisk cavity as illustrated in Fig. 1(a). Such surface mode guided WGM on PC microdisk can has a much higher Q factor than the SPP-guided WGM that suffers from the metal loss. In this letter, we study their optical properties and demonstrate lasing in PC microdisk cavities fabricated on GaAs substrate with InGaAs quantum dots as gain media emitting at around 1 μm.

The properties of surface modes in 1D PC structure as depicted in Fig. 1(a) are studied by transfer matrix method calculations.[11] The properties of PC microdisk cavities are studied by finite difference time domain (FDTD) simulations (FULLWAVE, RSoft Design Group). In all calculations and simulations, free space wavelength of 1000 nm is assumed and n_1 and n_2 are assumed as 3.1 and 3.5 for $Al_{0.9}Ga_{0.1}As$ and GaAs at the wavelength of 1000 nm. Surface mode can be guided only when the equivalent ε of PC is negative. The sign of equivalent ε at a specific wavelength is determined by the band structure plotted in Fig. 2(a) where $a=b=300$ nm is chosen for supporting surface mode with relatively large effective index. A 1D PC with infinite number of periods can serve as a perfect Bragg reflector in the forbidden bands. Just like ideal metal can serve as a perfect reflector because of its purely negative ε, the perfect Bragg reflector formed by 1D PC also posses equivalent ε being purely

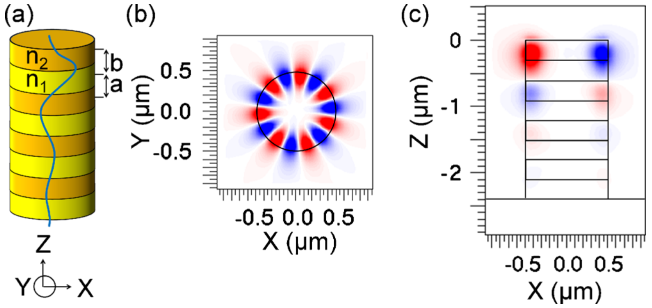

FIG. 1. (Color online) (a) PC microdisk cavity supporting surface mode guided WGM. n_1 and n_2 denote the two refractive indices; a and b are the thickness of dielectric bilayers in each period of PC. The sketched curves represent the surface modes guided in the PC layers in the transverse direction. (b) The lateral and (c) transverse cavity mode profile (hertz) of the structure in (a) with four periods and disk diameter of 1000 nm when $n_2=3.5$, $n_1=3.1$, and $a=b=300$ nm.

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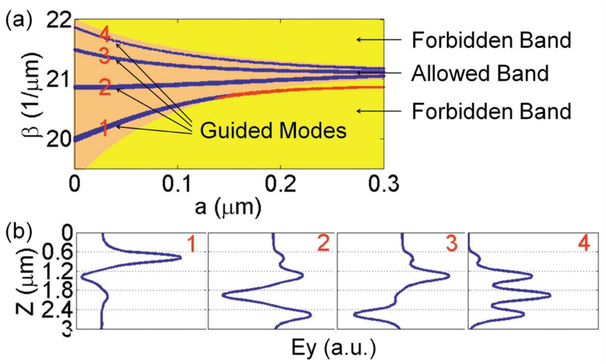

FIG. 2. (Color online) (a) Band structure of infinite 1D PC for TE waves (electric field in y direction) $n_2=3.5$, $n_1=3.1$, and $a=b=300$ nm, where the forbidden and allowed bands are illustrated. The guided modes for finite 1D PC of four periods are illustrated by curves numbered from 1 to 4. (b) Transverse electric field distribution for each guided mode. For mode 1, 2, 3, and 4, the calculated mode sizes are 0.245λ, 0.482λ, 0.523λ, and 0.565λ and the confinement factors are 0.078, 0.017, 0.018, and 0.006 respectively.

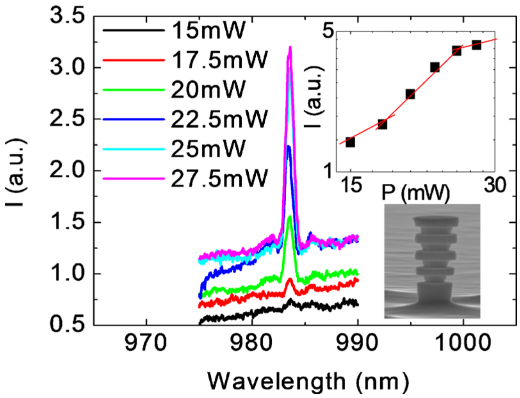

FIG. 3. (Color online) Evolution of lasing peaks from PC microdisk with four layer of GaAs/AlGaAs (300 nm thick for each layer) and diameter of about 1200 nm. The inset shows peak intensity vs pump power showing typical knee features; and a SEM photograph of the fabricated PC microdisk.

real and negative in the forbidden bands, which leads to evanescent electromagnetic waves in the PC structure.

The evanescent field profile of the surface modes is ideally suited to construct confined cavity modes for lasers. We now show that such mode in a cylindrical cavity provides the smallest mode volume while maintaining a large overlap with the gain media. For 1D PC with finite number of periods, apart from the surface modes in the forbidden band, other propagating modes also exist in the allowed bands. Figure 2(a) shows the dispersion curves for all guided modes in the first band of 1D PC with four periods, with the corresponding field profiles shown in Fig. 2(b). For 1D PC with N periods, there are N guided modes associated with each band. Within each forbidden band, there is at most one guided mode corresponding to the surface mode in 1D PC. Among these, the surface mode has the smallest extension in the transverse direction and this mode size is 0.245λ. The tight transverse confinement of the surface mode can help to reduce the overall cavity mode volume which in turn reduces the threshold modal gain. Moreover, since the modal gain is the product of material gain and confinement factor, a larger confinement factor leads to a lower threshold material gain for the same modal gain threshold required for lasing. The confinement factor of each mode is calculated by assuming four layers of gain material of 5 nm thick with 10 nm thick spacer placed at the center of the very top n_2 layer. It is found that the surface mode has a confinement factor of 0.078 which is at least four times larger than other guided modes in Fig. 2(b). This means that threshold material gain for surface mode is at least four times smaller than other guided modes. Although the propagation constant of surface mode is smaller than other guided modes and this could lead to a larger radiation loss, the reduction is at most 20% on the cavity Q factor for a microdisk of 1 μm in diameter and can be well remedied by the larger difference in the confinement factor and mode size. In comparison, the fundamental mode size of a single disk layer of equal total thickness [4×b, where b is illustrated in Fig. 1(a)] is 2.6 times larger and the confinement factor is 3.3 times smaller the surface mode in PC cavity. The small mode volume and large confinement factor provided by surface mode in 1D PC makes it suitable for providing transverse confinement for microdisk cavity. The cavity mode of PC microdisk is simulated by FDTD with lateral and transverse mode profile shown in Fig. 1(b). The mode volume is only $0.05\lambda^3$ due to small mode size in the transverse direction and the cavity Q factor reaches over 30 000, which is more than 100 times larger than metal-capped microdisk.[7]

To demonstrate the feasibility of semiconductor laser based on PC microdisk cavity, cavity structures were fabricated with four pairs of $Al_{0.9}Ga_{0.1}As/GaAs$ bilayers grown on GaAs substrate by MBE and with four InAs quantum dots layers embedded in the GaAs layers with a spacing of 15 nm. Microdisk cavities were patterned by electron-beam lithography and dry etched 2.5 μm deep to form four stacks of bilayers as illustrated in Fig. 1(a). The $Al_{0.9}Ga_{0.1}As$ layers are wet etched with buffered hydrogen fluoride (HF) to introduce larger index contrast with GaAs as shown in the inset of Fig. 3. The fabricated PC microdisks were pumped by 780 nm pulsed laser with pulse width of 100 fs and repetition rate of 80 MHz. The surface mode in the transverse dimension could be excited by the spontaneous emission and form WGM in the lateral plane of the microdisk. The sample was cooled to 77 K in a liquid nitrogen cryostat. The emission spectrum measured by InGaAs detector showed photoluminescence from InAs quantum dots centered at about 1 μm. Development of peaks was observed for PC microdisks of diameter as small as 1.1 μm (Fig. 3). The sharp peak of width smaller than 1 nm demonstrated the lasing behavior when power from pump laser is larger than 15 mW. The actual power absorbed by individual PC microdisk is much less.

In conclusion, we demonstrated a type of microdisk laser with transverse confinement provided by the PC surface mode and lateral confinement by WGMs. The surface mode supported by PC in the transverse dimension features small mode size, large confinement factor, and no additional propagation loss other than the radiation loss of WGM in the lateral plane. The cavity mode in PC microdisk has low threshold material gain and therefore, low threshold pump power. Our experimental results prove that such laser with structure sizes in all three dimensions about wavelength scale can lase at low pump power.

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