OPTOELECTRONICS LETTERS Vol.7 No.4, 1 July 2011

Luminescence enhancement from Si-based materials by introducing a photonic crystal double-heterostructure slot waveguide microcavity*

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(Received 31 March 2011)

We demonstrate a novel SOI-based photonic crystal (PC) double-heterostructure slot waveguide microcavity constructed by cascading three PC slot waveguides with different slot widths, and simulate the luminescence enhancement of sol-gel Er-doped SiO_2 filled in the microcavity by finite-difference time-domain (FDTD) method. The calculated results indicate that a unique sharp resonant peak dominates in the spectrum at the expected telecommunication wavelength of 1.5509 μm, with very high normalized peak intensity of $\sim 10^8$. The electromagnetic field of the resonant mode exhibits the strongest in the microcavity, and decays rapidly to zero along both sides, which means that the resonant mode field is well confined in the microcavity. The simulation results fully verify the enhancement of luminescence by PC double-heterostructure slot waveguide microcavity theoretically, which is a promising way to realize the high-efficiency luminescence of Si-based materials.

Document code: A **Article ID:** 1673-1905(2011)04-0266-3

DOI 10.1007/s11801-011-1023-x

The realization of Si-based laser is the core in the whole Si-based optoelectronics field. But Si is a poor light emitter due to its indirect band-gap, and the high-efficiency luminescence from Si has become one of the most challenges in group IV photonics. Doping SiO_2 with erbium (Er) ions is a possible way to obtain a radiative transition. Nevertheless, the light emission from current Er-doped SiO_2 materials is too weak for practical applications. There are many methods proposed to fabricate Er-doped SiO_2 materials, among which the sol-gel[1] technology has attracted much attention, which has the advantages of low operating temperature, accurate control of doping, high concentration and uniformity of doping, etc.

Photonic crystals (PCs)[2-4] have been shown to be an excellent means of controlling the interaction between light and matter. By introducing some point defects in perfect PC structures to form microcavity, the enhancement of luminescence at the resonant frequency can be realized by the mode confinement effect of microcavity[5-9]. Additionally, the spontaneous radiation also can be enhanced by PC band-edge slow-light effect[10,11], which can raise photon state concentration. The slot waveguide structures[12] consisting of bilateral high-refractive-index media and central low-refractive-index slot have strong field confinement effect, which can strengthen the interaction between light and media filled in the slot. If the microcavity can concentrate the properties of PC mode confinement effect, slow-light effect and slot strong field confinement effect, the interaction between light and Si-based luminance materials filled in the microcavity can be strengthened substantially, and the light emission efficiency can be enhanced dramatically.

In this paper, we analyze the dispersion of two-dimensional SOI-based planar PC slot waveguides (SPCWs) with different slot widths by the two-dimensional plane-wave expansion (2D-PWE) method. According to the calculated results, we propose a novel PC double-heterostructure slot waveguide microcavity constructed by cascading three dif-

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* This work has been supported by the National Key Basic Research Special Fund of China (No.2007CB613404), the National High Technology, Research and Development Program of China (No.2011AA010303), and the National Natural Science Foundation of China (Nos.61090390, 60837001, 60977045, 60877014 and 60776057).

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ferent SPCWs, with sol-gel Er-doped SiO_2 materials filled. The enhancement of luminescence is verified by the two-dimensional finite-difference time-domain (2D-FDTD) method theoretically.

The SPCW discussed here is formed by introducing a slot in the center of a 2D planar hexagon PC waveguide (PCW) along Γ-K direction on SOI substrate (220 nm-thick top silicon, n=3.5; 1 μm-thick buried oxide, n=1.45), with sol-gel Er-doped SiO_2 materials (n=1.45) filled in the slot and air-holes, whose cross-section diagram is shown in Fig.1. Fig.2 shows the schematic structure of SPCW, where w, w_s, a, r and R represent PCW width, slot width, lattice period, radii of air-hole non-adjacent and adjacent to slot, respectively.

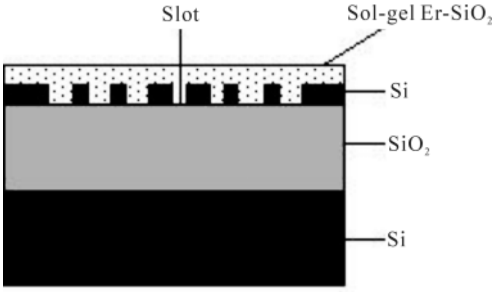

Fig.1 Cross-section of a SPCW filled with sol-gel Er-doped SiO_2

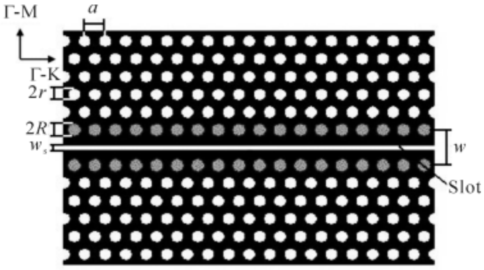

Fig.2 Schematic structure diagram of the SPCW

To simplify calculation, we calculate the effective refractive index (2.872) of the fundamental mode for SOI-based planar waveguide by effective refractive index method first, changing quasi-3D PC structure to equivalent pure 2D structure. Then the dispersion curves with slot widths increasing from $0.3a$ to $0.4a$ for the 2D SPCW are calculated, where r/a and w are set to be 0.3 and $\sqrt{3}a$, respectively, and R/a is set to be 0.36 for achieving flatter band-edge. The calculated result shown in Fig.3 indicates that there is a unique guided mode transmitted in the SPCW, with close-to-zero group velocity at the normalized frequencies around the band-edge, and the dispersion curve moves to high frequency direction wholly with the slot width increasing.

According to the result, we demonstrate a novel PC double-heterostructure slot waveguide microcavity based on PC mode-gap effect[13,14], as shown in Fig.4. The microcavity is formed by cascading three SPCWs with different slot widths, named SPCW1, SPCW2 and SPCW3, successively, and the microcavity has bilateral hetero-interfaces. The slot width of SPCW1 is the same as that of SPCW3, represented as w_s, but it is narrower than that of SPCW2, represented as w_s'. The mode with certain normalized frequency is confined in the central SPCW2 microcavity due to the mode-gap effect, and the group velocity of the confined mode also can be confined to a low value close to zero due to the flat dispersion curve in the mode-gap, which can raise photon state concentration. Meanwhile, the mode field in the microcavity can be further strengthened by slot strong field confinement effect. Therefore, the novel microcavity structure, which has mode-gap mode confinement effect, slow-light effect and slot strong field confinement effect simultaneously, can strengthen the interaction between light and Er-doped SiO_2, and thus can enhance the luminescence efficiency of Er-doped SiO_2 substantially.

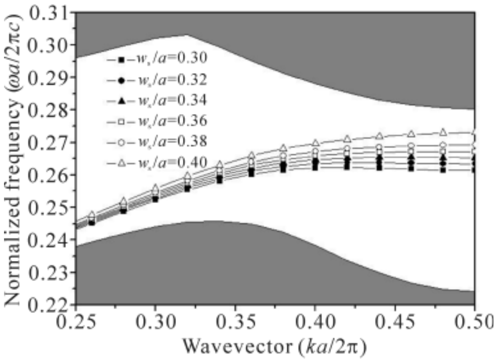

Fig.3 Calculated dispersion curves with different slot widths for the 2D SPCW

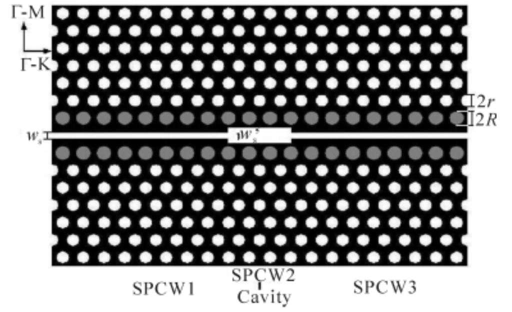

Fig.4 Schematic diagram of the PC double-heterostructure slot waveguide microcavity

Through optimizing design, we set a=408 nm, r/a=0.3, R/a=0.36, $w=\sqrt{3}a$, w_s=0.3a, and w_s'=0.36a, respectively. The resonant spectrum and resonant mode field of the central microcavity are simulated by 2D FDTD method, whose results are shown in Fig.5 and Fig.6, respectively. In Fig.5, a satisfactory resonant spectrum is achieved, in which a unique sharp resonant peak dominates at the expected telecommunication wavelength of 1.5509 μm, with very high normalized peak intensity of ~10^8. In Fig.6, the electromagnetic field of the resonant mode exhibits the strongest in the central microcavity, and decays rapidly to zero along both sides, which means that the resonant mode is well confined in the microcavity. This result fully verifies the enhancement of luminescence for Er-doped SiO_2 by PC double-heterostructure slot waveguide microcavity theoretically, which is a promising way for realizing high-efficiency luminescence of Si-based materials.

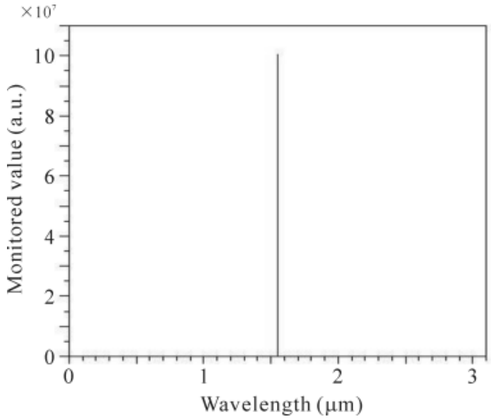

Fig.5 Resonant spectrum of the microcavity

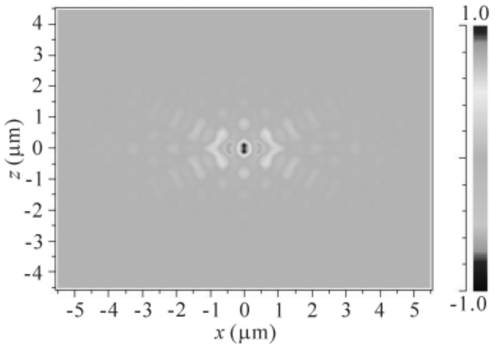

Fig.6 Resonant mode field distribution of the microcavity

In conclusion, the design of a novel PC double-heterostructure slot waveguide microcavity for enhancing luminescence from sol-gel Er-doped SiO_2 materials filled in the microcavity is proposed in this paper, which has mode-gap mode confinement effect, slow-light effect and slot strong field confinement effect simultaneously. The high-efficiency luminance enhancement at 1.5509 μm telecommunication wavelength is verified by the simulation. The PC double-heterostructure slot waveguide microcavity structure explores a novel approach for Si-based high-efficiency luminance, which has huge research and application potential in Si-based optoelectronics integration.

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