

# Study of optical gain from square-nested PCFs with impurities

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Using numerical simulation method based on finite-difference time-domain (FDTD), we study the characteristics of the multiple-core photonic crystal fibers (PCFs) in which square-nested compound lattices (SNCLs) with several defect regions are introduced. We find that each line defect in the PCFs can serve as a channel in wavelength division multiplexing (WDM) communication systems. The crosstalk can be suppressed because there is a band gap among each channel in the PCFs. And PCF amplifiers are expected to be used in the super-dense WDM systems.

OCIS codes: 060.2280, 230.0230, 120.4570, 160.2290.

More and more interest has been attracted to the behaviors of electromagnetic wave propagating in man-made periodic dielectric materials, called photonic crystals, in recent years<sup>[1-3]</sup>. When impurities are introduced into photonic crystals properly, new electromagnetic localized modes can be created in photonic band gaps, and the position and width of the energy gap as well as the mode of impurity can also be controlled. As a result, narrow transmission bands with superhigh transmissivity can be obtained and crosstalk can be suppressed because of the existing of photonic band gaps outside of the transmission bands.

In the paper the transmission channels, resulting from two-dimensional (2D) photonic crystal fibers (PCFs) in which square-nested compound lattices (SNCLs) with several defect regions are introduced and, are studied with finite-difference time-domain (FDTD) method. And we find out the relation between the enhancement of stimulated emission as well as the transmittivity and the abnormal group velocity in photonic forbidden gaps as well as the negative imaginary component of the complex effective index of refraction of doped medium. Crosstalk can be suppressed because of the existing of a band gap among each channel in the PCF. Therefore, PCF amplifiers used in the super-dense wavelength division multiplexing (WDM) systems can be developed in the near future.

From the definition of group velocity<sup>[4]</sup>  $v_g = (dk/d\omega)^{-1}$ , we have

$$v_g = \left[ \frac{d(\omega n/c)}{d\omega} \right]^{-1} = c / \left[ n(\omega) + \omega \frac{dn(\omega)}{d\omega} \right]. \quad (1)$$

The mode density  $\rho(\omega)$  stands for  $dk(\omega)/d\omega$  in the Ref. [5],

$$\frac{dk(\omega)}{d\omega} = (6\pi^2)^{1/3} \rho(\omega) \left[ \int_0^\omega \rho(\omega') d\omega' \right]^{2/3}. \quad (2)$$

It shows that, in the finite periodic doped structure, the group velocity of electromagnetic wave traveling in a photonic crystal is directly proportional to the inverse of the mode density.

Therefore, the complex effective refractive index of the

doped defect above-mentioned is<sup>[6]</sup>

$$n_d = n_{\text{eff}}(\omega) = n(\omega) + is(\omega), \quad (3)$$

where  $n(\omega)$ , the real component of the complex active refractive index, stands for the nature of equivalent dispersion, and  $s(\omega)$  denotes the absorption of the doped layer.

The cross sections of the PCFs employed in our paper are shown schematically in Figs. 1-4. The PCFs are infinite cylindrical structures along their axes made up of the same matrix of InP/GaInAsP with a refractive index  $n = 3.24$  in which SNCLs (lattice constant is  $a$ ) with several different kind of defects are introduced.

As shown in Fig. 1(a), the SNCLs are made of air holes with the same radius  $r = 0.4a$  and one doped defect with refractive index  $n_2 = 3.4$  in the center. As a result, localized photonic defect modes are created in the ordered photonic band gaps, i.e., several transmission peaks with rather small amplitudes come out in photonic band gaps, as shown in Fig. 1(b). Another kind of SNCLs are also made of air holes, but the radii of the eight air holes around its center are decreased to  $r = 0.3a$  (see Fig. 2(a)), forming new doped defects. Obviously the transmission is enlarged and even a transmission peak is up to one. Based on Fig. 2(a), the radii of another forty air holes around its center are decreased to  $r = 0.3a$  (see Fig. 3(a)). Comparing Fig. 2(b) with Fig. 3(b), we find out that the transmission peaks and the optical gain increase with increasing doped defects introduced into SNCLs, and that there are more localized photonic defect modes in band gaps.

When the forty-nine air holes inside the structure

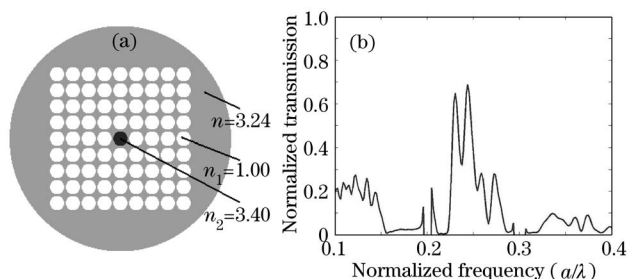


Fig. 1. Schematic cross section of a PCF with  $n_d = 3.4$ ,  $s=0$  (a) and its transmission spectrum (b).

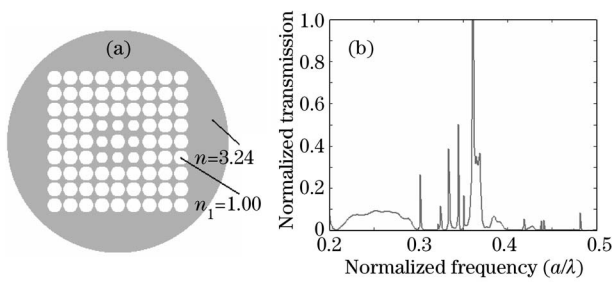


Fig. 2. Schematic cross section of a PCF with  $n_d = 1$ ,  $s = 0$  (a) and its transmission spectrum (b).

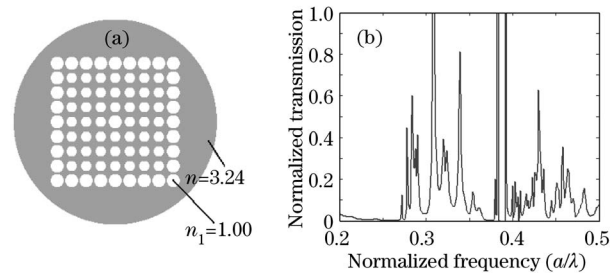


Fig. 3. Schematic cross section of a PCF with  $n_d = 1$ ,  $s = 0$  (a) and its transmission spectrum (b).

of Fig. 3(a) are replaced by active impurities (i.e., Er), shown in Fig. 4(a), the imaginary component of  $n_d$  is not being zero any more, but a negative value. From Fig. 4, we can find obviously that the enhancement of stimulated emission occurs at some particular frequencies and that the transmission is greater than one and that the number of localized photonic defect modes increases. According to Eq. (1), the group velocity of optical pulse with frequency near that of the defect mode is much more smaller than that of PCF without defects of active impurities because the group velocity  $v_g$  drops with the increasing of  $dn/d\omega$ . Based on Eq. (2), the corresponding mode density of photon is enhanced dramatically and the optical gain increases notably due to the imaginary component of the complex effective refractive index of the doped active

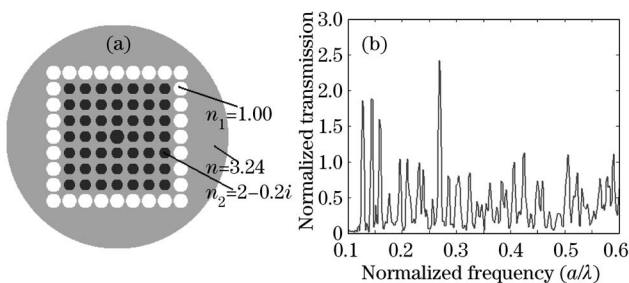


Fig. 4. Schematic cross section of a PCF with  $n_d = 2.2 - 0.2i$  (a) and its transmission spectrum (b).

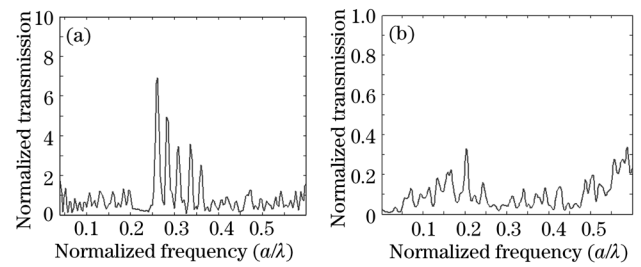


Fig. 5. Transmission spectra of PCF with the same structure as that in Fig. 4(a), but  $n_d = 2 - 0.3i$  (a) and  $n_d = 2 + 0.2i$  (b).

impurities  $s < 0$ , which illustrates that the transmission can be much greater than one.

By making a comparison between Fig. 4(b) and Fig. 5(a), we find that the bigger the absolute value of  $s$  of complex effective refractive index is, the larger the transmission and the optical gain become. Comparing Fig. 4(b) with Fig. 5(b), we notice that, when  $s$  varies from a positive value to a negative one, the transmission from a value greater than one to a value less than one, and that the doped impurities behave as from optical amplification to optical absorption. The results further prove that the media doped with active impurities are optical gain media, which lead to light being highly localized and the corresponding mode density of photon being enhanced dramatically.

In conclusion, transmission spectra of PCFs with different kind of defects are presented in the paper. With active impurities introduced into photonic crystals properly, doped modes with very high quality factors and great mode density are formed in the photonic band gaps and amplification of spontaneous emission can be realized. So separated transmission spectra can be obtained by increasing doped defects introduced into SNCLs. It means the PCFs can be made into optical amplifiers to be employed in the super-dense WDM communication systems to increase the bit rate-distance product.

This work was supported by the Natural Science Foundation of Jiangsu Province of China (No. BK2004059). Z. Li's e-mail address is lih harder@vip.163.com.

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