Enhanced nonlinearity in photonic crystal fiber by germanium doping in the core region

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Germanium doping in silica can be used as a method for nonlinearity enhancement. Properties of the enhanced nonlinearity in photonic crystal fiber (PCF) with a GeO_2-doped core are investigated theoretically by using all-vector finite element method. Numerical result shows that the nonlinear coefficient of PCF is greatly enhanced with increasing doping concentration, furthermore, optimal radius of the doped region should be considered for the desired operating wavelength.

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Recent years, a novel waveguide in the form of photonic crystal fiber (PCF) has attracted considerable interests and offered widespread applications due to its unique properties[1,2]. One of the promising practical fields is fiber nonlinearity. With the high index contrast between silica and air, the microstructure fiber can be designed with a smaller core area allowing stronger mode confinement, thus having higher nonlinearity[3−5]. Moreover, by properly designing, it can provide low dispersion and dispersion slope characteristics at desired wavelength range[6]. Abundant nonlinear phenomena can be observed in such kind of fiber with relative short length compared with conventional fiber[7]. However, as the dimension of the fiber core is decreased to or less than the operating wavelength, a so-called “evanescent” situation occurs. In other words, the distribution of the modal field leaks into the air cladding region, and is no longer well confined in the silica core. So fiber nonlinearity cannot be enhanced illimitably by simply reducing the area of the core. Study shows that germanium doping in silica can enhance the material nonlinear index of refraction and has been applied as a mature technique for fabricating conventional high nonlinear (HN) fiber[8]. Thus such a method may also be employed in pure silica HN-PCF for further nonlinearity enhancement. In this letter, properties of nonlinearity of HN-PCF with pure silica core and GeO_2-doped core are theoretically studied using a finite element method. Result shows that with the cooperation of the enhanced nonlinear refraction index and the more confined modal field distribution, the nonlinear coefficient of the PCF is greatly enhanced compared with pure silica situation. Furthermore, the concentration and the area of the doped region also have influence on the fiber's nonlinearity.

We take all-vector finite element method as our simulative tool. It is a powerful numerical method and meets the requisition for modeling microstructure fibers with complex configuration. In the simulation, a kind of nonlinear PCF with hexagon air holes in cladding region is considered, and it has been successfully fabricated by crystal-fiber A/S[9]. The sketch map of the nonlinear PCF is illustrated in Fig. 1, which contains a small solid silica core, surrounded by a microstructure cladding formed by periodic hexagonal air holes. The fuscous circle concentric with the fiber's axis represents the GeO_2 doping region, and the radius of the doped area is marked as r_D. In Fig. 1(b), a denotes the radius of air holes, and d is the width of silica wall (struts holding the core).

For conventional fiber, the nonlinear coefficient is usually defined as $\gamma = 2\pi n_2/(\lambda \cdot A_{\text{eff}})$, where A_{eff} is the effective modal area and n_2 is the nonlinear index coefficient of pure silica. However, considering the overlapped field with materials which are of different nonlinear index of refraction, the modified definition of effective nonlinear mode area of PCF should be adopted for the doped situation

$$A_{\text{eff}} = \frac{n_2(\iint E(x,y)E^*(x,y)\mathrm{d}x\mathrm{d}y)^2}{\iint \tilde{n}_2(x,y)[E(x,y)E^*(x,y)]^2\mathrm{d}x\mathrm{d}y},$$

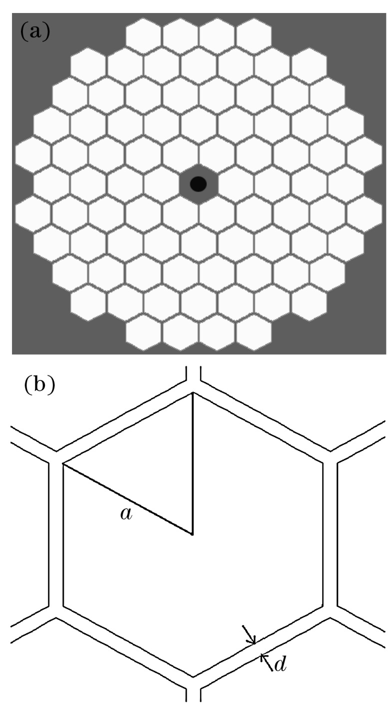

Fig. 1. Sketch map of nonlinear PCF with Germanium doping in the core region.

where $E(x,y)$ is the transverse electric field, and $\tilde{n}_2(x,y)$ is the nonlinear index coefficient of the material at position (x,y)[4]. The refractive index and nonlinear index coefficient for pure silica are 1.446 and 2.507×10^{-20} m^2/W, respectively. From Ref. [10], the relationship between relative index difference and the nonlinear refractive index in GeO_2-doped bulk glass can be experimentally expressed as $\tilde{n}_2 = 2.507+0.505\delta$. We define the relative index difference as $\delta = (n_1^2 - n_0^2)/2n_1^2$, where n_0 and n_1 denote the refractive indexes of pure SiO_2 and the doped glass, respectively. Note that the above-mentioned relationship is obtained for operating wavelength of 1550 nm. As the wavelength changes, $\tilde{n}_2$ has a slight variation. However, the variation is smaller by two orders of magnitude and need not be taken into account for simplicity[11].

From Fig. 1, the diameter of the silica core for pure silica PCF can be evaluated as $(\sqrt{3}a + 2d)$. For the fixed operating wavelength, either decrease of the two parameters will confine the mode distribution within a smaller area in the silica core until the diameter of the core is less than the wavelength scale, where the distribution of the fundamental mode is not confined within the silica core and expands beyond into the air region. Thus appropriate parameters should be chosen to ensure the smaller silica core whilst well confining the mode distribution. For comparison, $a = 1.2$ μm and $d = 0.12$ μm are adopted throughout the studies. The lowest curve in Fig. 2 gives the nonlinear coefficient γ as a function of operating wavelength for pure silica PCF. From the curve, γ is 77 $km^{-1}\cdot W^{-1}$ at wavelength of 800 nm, which is in accordance with that of the actual fiber[9]. Inset is the tightly confined mode distribution of the fundamental mode.

As for the doped situation, the fiber's nonlinear coefficient γ relative to the wavelength for different index contrast according to varying doping concentration is shown in Fig. 2 (r_D is fixed at 0.8 μm). Compared with the pure silica fiber ($\delta = 0$), great enhancement of fiber nonlinearity can be seen due to the cooperation of enhanced material nonlinear index $\tilde{n}_2$ and more confined modal field because of the enhanced refractive index contrast. For the fixed operating wavelength, the nonlinear coefficient of the fiber presents monotonic increase with the enhancement of the doping concentration in the calculated wavelength region. Furthermore, the increase is more obvious in short wavelength region than that in longer wavelength region. It can be contributed to the more confined mode field distribution in short wavelength resulted from the effect of the rising difference of linear index, where the mode field overlapped more with higher $\tilde{n}_2$ value, thus having higher level of fiber nonlinearity. For the fixed doping region and well confined mode field distribution, the higher the doping concentration, the larger the fiber's nonlinear coefficient. Figure 3 shows that for fixed operating wavelength, fiber nonlinear coefficient increases almost linearly with the enhanced relative index difference. At present, PCF containing highly GeO_2-doped core with an index difference of $\sim$ 1.06% has been reported[12]. With the gradually improved technique of fiber doping and fabrication, fiber nonlinearity can be further enhanced in HN-PCF by doping GeO_2 in the small core region.

The above discussion is carried out under the condition of invariable value of r_D. From the modified definition of the doped fiber's nonlinear coefficient, γ relates to the overlapped integration between the mode field and the nonlinear index coefficient of material $\tilde{n}_2(x,y)$. On the one hand, the change of r_D impacts on the distribution of $\tilde{n}_2(x,y)$. On the other hand, it can also act on the distribution of the mode field by changing the linear refractive index contrast of the waveguide. With such cooperation, the behavior of γ relative to r_D is complicated, and is necessary to be investigated. Under the condition of the well confined mode area, the reducing r_D leads to more confined distribution of mode field for the fixed operating wavelength. Although the area of doped region with relatively high $\tilde{n}_2$ is shrinking, the overlap between the mode field and the nonlinear index coefficient of material

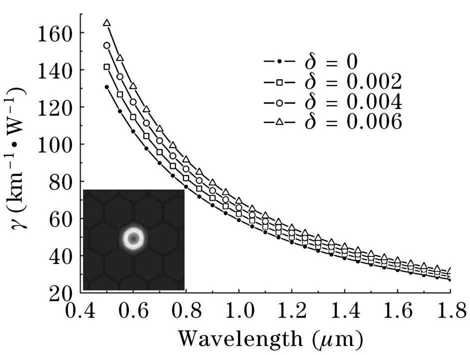

Fig. 2. Nonlinear coefficient as a function of wavelength for different index contrast between silica bulk and doped core, a, d, and r_D are 1.2, 0.12, and 0.8 μm, respectively.

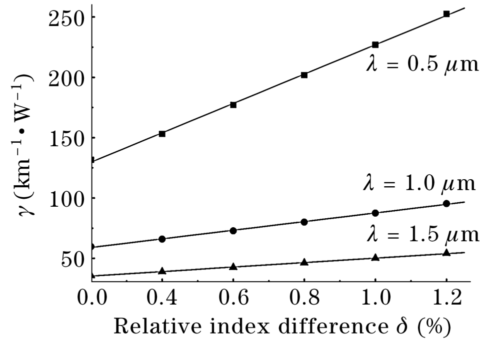

Fig. 3. Nonlinear coefficients of the doped HN-PCF relative to refractive index difference δ.

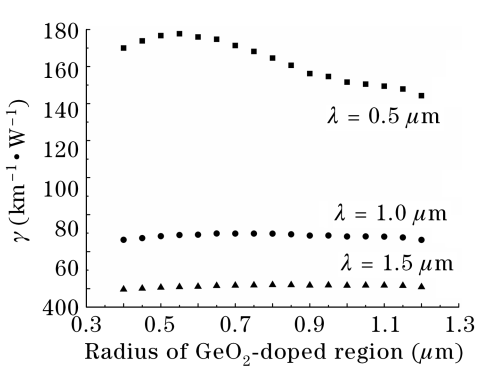

Fig. 4. Influence of r_D on nonlinear coefficients for special operating wavelengths.

is enhanced. However, as r_D reduces to a value where the distribution of the mode field severely lies out of the doped region, the overlapped field with relatively high $\tilde{n}_2$ of the doped region is weakened. Fiber's nonlinear coefficient as a function of radius of GeO_2-doped region is shown in Fig. 4. The index difference δ is fixed and the calculated wavelengths are 0.5, 1.0, and 1.5 μm, respectively. The phenomenon is not so obvious for long wavelength compared with short wavelength. However, it is true that optimal r_D should be chosen to realize maximal fiber nonlinear coefficient.

In conclusion, nonlinear coefficient of PCF can be greatly enhanced by introducing GeO_2-doped region in the center of the silica core. With a finite element method, properties of nonlinearity of HN-PCF before and after doping are studied theoretically. The results show that raising the concentration of the adulterant is beneficial for enhancing the fiber nonlinearity. Furthermore, optimal radius of the doped region should be considered for the desired operating wavelength.

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