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• **LETTER** •

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Design method for low index trench and rod assisted weakly-coupled multi-core fiber

Jiajing TU & Keping LONG*

Beijing Engineering and Technology Research Center for Convergence Networks and Ubiquitous Services, University of Science and Technology Beijing (USTB), Beijing 100083, *China*

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Dear editor,

As a solution of space-division multiplexing, multi-core fibers (MCFs) are used to further increase the transmission capacity of optical fiber thanks to the increased spatial channels, compared with single-core fiber (SCF) [1]. MCF can be generally classified as weakly-coupled MCF and strongly-coupled MCF [2]. For weakly-coupled MCF, cores are deployed with sufficiently large core-to-core distance so that each core can be treated as an independent spatial channel with low inter-core crosstalk [3] and for strongly-coupled MCF, super-modes can be excited due to the large inter-core crosstalk, which is caused by extremely small core-to-core distance [2].

In this letter, we mainly focus on the weakly-coupled MCF. In the weakly-coupled MCF, how to suppress the inter-core crosstalk is an important issue [3]. The most widely used method is adding low index trench around each core to suppress the overlap of electric field distribution and so far various trench-assisted MCFs have been investigated and fabricated [4–7]. However, the size of trench is much influenced by the size of core, since the relative position and width of the trench are usually assumed to have a proportional relation with core radius. Trench size which is decided by the core radius will increase the confinement degree of light so that the cable cutoff wavelength (λ_{cc}) of higher-order mode of cores will be lengthened, especially for the inner cores. Therefore, taking typical 7-core fiber as an example, we propose a design method for 1-trench and 6-rod assisted 7-core fiber. In order to make the design of cores easier, low index rod instead of trench layer is added in the middle of two adjacent outer cores and trench structure is still deployed around the center core.

Design of 1-trench and 6-rod assisted 7-core fiber. Figure 1(a) shows the cross section and index profile of 1-trench and 6-rod assisted 7-core fiber. In Figure 1(a), $r_{\rm o}$, $r_{\rm c}$, $r_{\rm d}$ and $r_{\rm t}$ represent core radii of outer core, center core, low index rod and the distance between core and inner edge of trench, respectively. $\Delta_{\rm o}$, $\Delta_{\rm c}$, $\Delta_{\rm t}$ and $\Delta_{\rm d}$ stand for the relative refractive index difference between outer core and cladding, that between center core and cladding, that between trench and cladding and that between rod and cladding, respectively. W is the width of the trench structure and Λ is the core-to-core distance. Now we fix the core radius of center core $r_{\rm c}$ at 4.0 μm, $\Delta_{\rm d}$ and $\Delta_{\rm t}$ at −0.7 %. Moreover, we assume that $r_{\rm t}/r_{\rm c} = 2.0$ and $W/r_{\rm c} = 1.0$. In the supporting Figure S1, we investigate the impact of $r_{\rm o}$ and Λ on the cutoff wavelength (λ_{cc}) for 7-trench assisted 7-core fiber. In the supporting Figure S2, we analyze how $r_{\rm d}$ and Λ influence the λ_{cc} for 1-rod and 6-trench assisted 7-core fiber. From S1 and S2, we can observe that when

* Corresponding author (email: longkeping@ustb.edu.cn)
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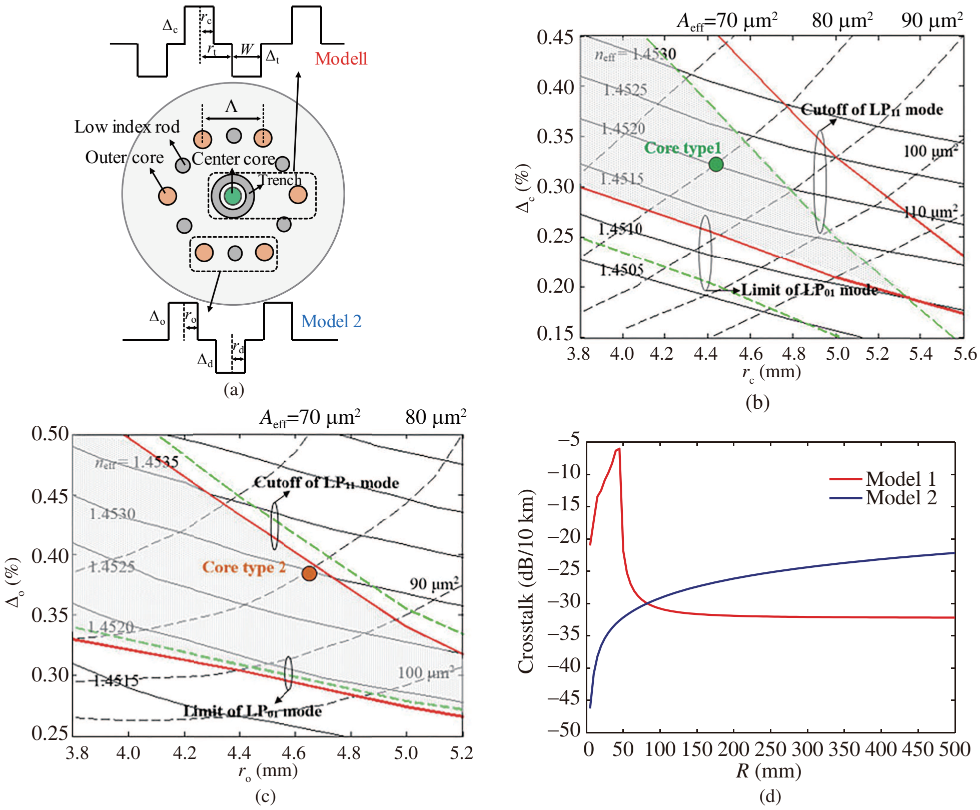

Figure 1 (a) Cross section and index profile of 1-trench and 6-rod assisted 7-core fiber; (b) $n_{\rm eff}$ and $A_{\rm eff}$ as functions of $r_{\rm c}$ and $\Delta_{\rm c}$ for center core; (c) $n_{\rm eff}$ and $A_{\rm eff}$ as functions of $r_{\rm o}$ and $\Delta_{\rm o}$ for outer core; (d) dependence of crosstalk on R after 10 km transmission.

Λ is smaller than 35 μm, $r_{\rm o}$ and $r_{\rm d}$ have big impact on $\lambda_{\rm cc}$ of higher-order mode in the center core. If we set Λ at 30 μm, the core radius of outer core in 7-trench MCF should be designed carefully to make sure $\lambda_{\rm cc} \leqslant 1530$ nm, which is the lowest limit of C+L bands. However, for the 6-rod 1-trench assisted MCF, the core radius of outer core will not influence the $\lambda_{\rm cc}$, which is affected by the size of low index rod. If Λ is 30 μm, we can set $r_{\rm d}$ at some value in the region of 4.0–8.0 μm, in which $r_{\rm d}$ has less impact on $\lambda_{\rm cc}$. Here, $\lambda_{\rm cc}$ is defined as the wavelength that makes the bending loss of $\rm LP_{11}$ mode approximate to 1 dB/m.

Since the size of outer core does not affect the $\lambda_{\rm cc}$ of center core, we design the center core firstly according to Figure 1(b), which shows effective area ($A_{\rm eff}$) and effective index ($n_{\rm eff}$) as functions of $r_{\rm c}$ and $\Delta_{\rm c}$. Here, we fix $\Delta_{\rm t}$ and $\Delta_{\rm d}$ at -0.7%. In Figure 1(b), black solid lines represent $n_{\rm eff}$ and black dash lines stand for $A_{\rm eff}$, which are simulated by finite element method [8]. According to the deployment configuration in IEC 60793-1-44 document, when macro bending loss (BL) of $\rm LP_{11}$ mode is not smaller than 1 dB/m at bending radius (R) of 140 mm and wavelength (λ) of 1.530 μm, it can be assumed that $\rm LP_{11}$ mode almost escapes away from the core. BL of 1 dB/m at R of 140 mm and λ of 1.530 μm is treated as the cutoff condition of $\rm LP_{11}$ mode. Therefore, the upper green dash line and red solid line are the cutoff lines of $\rm LP_{11}$ mode at $r_{\rm d}$ of 8.0 μm and 4.0 μm, respectively. Moreover, according to ITU-T recommendations G.655 and G.656, when the BL of $\rm LP_{01}$ mode is not larger than 0.5 dB/100 turns at R of 30 mm and λ of 1.625 μm, we think that $\rm LP_{01}$ mode is totally confined inside the core. BL of 0.5 dB/100 turns at R of 30 mm and λ of 1.625 μm is regarded as the limit condition of $\rm LP_{01}$ mode. Hence, the lower green dash line and red solid line are the limit lines of $\rm LP_{01}$ mode at $r_{\rm d}$ of 8.0 μm and 4.0 μm, respectively. The region filled with pattern is the design region of center core at the range of 4.0–8.0 μm for $r_{\rm d}$. We select Core type 1 as the center core, whose $r_{\rm c} = 4.43$ μm and $\Delta_{\rm c} = 0.319$ %. Subsequently, we design the outer core with the center core fixed as Core type 1 according to Figure 1(c), which illustrates $A_{\rm eff}$ and $n_{\rm eff}$ as functions of $r_{\rm o}$ and $\Delta_{\rm o}$. In Figure 1(c), the meanings of black solid lines, black dash lines, red solid lines and green dash lines are the same as that in Figure 1(b). The region filled with pattern in Figure 1(c) is the design region of outer core at the range of 4.0–8.0 μm for r_d. Here, we select Core type 2 as the outer core, whose $r_o = 4.66$ μm and $\Delta_o = 0.384$ %.

After obtaining the core parameters, we investigate the inter-core crosstalk between center core and outer core which is designated as Model 1 and the inter-core crosstalk between two identical outer cores which is designated as Model 2. Eq. (1) is the crosstalk of Model 1 ($\mathrm{XT_{MDL1}}$) [7,9], in which, d, k and L mean the correlation length, the wave number in a vacuum and the transmission distance, respectively; K is the mean value of mode coupling coefficient (κ) between center core and outer core and κ is given by Eq. (2) [10], where, ω is an angular frequency of the sinusoidally varying electromagnetic fields and ε_0 is the medium permittivity. n_i and n_{cl} represent the refractive index of core i and cladding. $\boldsymbol{E}_i$ and $\boldsymbol{E}_j$ mean the amplitude of electric field distribution of core i in the core i and that of core j in the core i, respectively. r_{1-i} stands for the radius of core i; P is the total power flow [10]. δn_{eff} is the difference of equivalent effective index between the neighboring cores, which is written as Eq. (3). In Eq. (3), $n_{\mathrm{eff},i}$ is the effective index of Core i; $n_{\mathrm{eff},j}$ is the effective index of Core j; θ is an angle from the radial direction of the bend [4]. The expression of crosstalk of Model 2 ($\mathrm{XT_{MDL2}}$) can be expressed as Eq. (4) [4], in which, R is the bending radius; L is the transmission distance; β means the prorogation constant; Λ is the core pitch; κ is the mode-coupling coefficient. Figure 1(d) shows the dependence of crosstalk on bending radius (R) when $L = 10$ km. From Figure 1(d), we can find that R of 80 mm is the design requirement to achieve crosstalk of -30 dB/10 km transmission for both Model 1 and Model 2.

$$\mathrm{XT_{MDL1}} = \tanh\left[\frac{2K^2 dL}{1+(dk\delta n_{\mathrm{eff}})^2}\right], \tag{1}$$

$$\kappa = \frac{\omega\varepsilon_0}{4P}\int_0^{2\pi}\int_0^{r_{1-i}}(n_i^2-n_{cl}^2)\boldsymbol{E}_i^*\cdot\boldsymbol{E}_j\, r\,\mathrm{d}r\,\mathrm{d}\theta, \tag{2}$$

$$\begin{aligned}\delta n_{\mathrm{eff}} &= (n_{\mathrm{eff},i}-n_{\mathrm{eff},j}) + \frac{\Lambda}{R}[n_{\mathrm{eff},i}\cos\theta_i(z)\\ &\quad -n_{\mathrm{eff},j}\cos\theta_j(z)],\end{aligned} \tag{3}$$

$$\mathrm{XT_{MDL2}} = \frac{2\kappa^2 RL}{\beta\Lambda}. \tag{4}$$

Conclusion. We proposed a kind of low index trench and rod assisted weakly-coupled MCF and gave the design method for this MCF. If core-to-core distance is 30 μm and bending radius equals 80 mm, the crosstalk between identical outer cores and that between non-identical outer core and center core are almost the same and the inter-core crosstalk can achieve -30 dB/10 km.

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Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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