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Role of wavelength dependent sensitivity in affecting the crosstalk mitigation of homogeneous multicore fiber: an analytical estimation approach

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Abstract: The mitigation of both crosstalk and its wavelength dependent sensitivity for homogeneous multicore fiber (MCF) is theoretically investigated using an analytical evaluation approach. It is found there exists a performance trade-off between the crosstalk mitigation and its wavelength dependent sensitivity suppression. After characterizing the fabricated homogeneous MCFs, we verify that although the increasing core pitch can mitigate the crosstalk, the wavelength dependent sensitivity is drastically degraded from 0.07dB/nm to 0.11dB/nm, which is harmful to the dense wavelength division multiplexing (DWDM) transmission over C + L band using MCF.

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References and links


1. Introduction

In order to satisfy the exponentially increasing bandwidth demands, optical signals are multiplexed in time, wavelength and polarization, together with multi-level modulation, almost reaching the Shannon limit of a single mode fiber (SMF) [1]. The multicore fiber (MCF) is a promising candidate for space division multiplexing (SDM) that can overcome the capacity crunch of SMF. However, one of the most important properties of MCF is the inter-core crosstalk (XT) and the technique to reduce the crosstalk is an inevitable issue. So far, theoretical investigations have been intensively conducted in the past few years [2–8]. The fiber bending effects on the crosstalk were investigated by introducing the equivalent refractive index model into the coupled mode theory and an approximation model for estimating the crosstalk distribution was presented [2–4]. An analytical equation was derived to evaluate the average power coupling coefficient based on an exponential autocorrelation assumption together with the coupled power theory [6,7]. Moreover, the dependence of crosstalk on the fiber length was calculated by assuming random fluctuations on the fiber structure along the longitudinal direction [8]. In brief, the dependence of crosstalk on these factors, such as bending, twist, longitudinal length and structure parameters, has been investigated theoretically and experimentally.

Meanwhile, SDM transmissions using MCF with low crosstalk design have also been experimentally demonstrated on high-capacity transmission beyond 100 Tb/s, especially with dense wavelength division multiplexing (DWDM) technique [9–12]. It is found that, different from the traditional DWDM transmission, the signals in the L-band have more optical signal-to-noise ratio (OSNR) penalty than that in the C-band due to the wavelength dependent crosstalk [9,10]. Such property is obviously detrimental to explore the C + L band transmission through the MCF. The wavelength dependence of mean crosstalk was experimentally found to be almost linearly increasing with respect to the operation wavelength [4,13]. The slopes of wavelength dependent crosstalk, which we define as wavelength sensitivity of the crosstalk (WS-XT), are different with respect to the MCF design [2,10,11]. To the best of our knowledge, there exists almost no in-depth investigation for the WS-XT of MCF, especially the optimization of MCF structural parameters on the WS-XT. For instance, if the WS-XT is reduced by 0.06dB/nm, then the crosstalk in L-band can be reduced by about 3dB, indicating that the crosstalk-limited transmission distance in L-band can be doubled on the condition of the same crosstalk penalty, due to the crosstalk linear dependence on the transmission distance [8,10].

In this paper, the mitigation of both crosstalk and its wavelength dependent sensitivity for homogeneous multicore fiber (MCF) is theoretically investigated using an analytical
evaluation approach. Then, we analytically investigate the influences of MCF structural parameters on the WS-XT, and find that there exists a performance trade-off between the suppression of WS-XT and the crosstalk mitigation. The experimental characterization is conducted to verify this theoretical conclusion.

2. Analytical investigation

In order to suppress the crosstalk, either the heterogeneous MCF or homogeneous MCF utilizing the phase mismatch induced by the bend is highly preferred [4]. Meanwhile, for the ease of theoretical derivation and easy fabrication, we choose the homogeneous MCF to start the investigation. The statistical mean of crosstalk between two adjacent cores of a homogeneous MCF can be expressed as [4]:

$$\langle XT \rangle = 2 \frac{RL\kappa^2}{\Lambda \beta}$$

(1)

where $R$ is the bending radius, $L$ is the fiber length, $\Lambda$ is the core pitch, $\kappa$ is the mode coupling coefficient and $\beta$ is the propagation constant. According to the optical waveguide theory, mode coupling coefficient $\kappa$ can be described as [14]:

$$\kappa = \sqrt{\Delta} \frac{U^2}{a} \frac{K_0\left(\frac{\Lambda W}{a}\right)}{K_1(W)}$$

(2)

where $\Delta$ is the relative refractive index difference, $a$ is the core radius, $U$ and $W$ are the normalized transverse wave number in the core and cladding, respectively, and $V$ is the normalized frequency. They can be expressed as [15]:

$$V = \frac{2\pi}{\lambda} n_a \sqrt{2\Delta}$$

(3)

$$W = 1.1428V - 0.996$$

(4)

$$V^2 = W^2 + U^2$$

(5)

$$\beta = \sqrt{\frac{W^2}{a^2} + n^2k^2}$$

(6)

Before we derive an analytical equation, we firstly make three approximations as follows, whose total error is less than 1% in the range of $1.7 \leq V \leq 2.4$. Firstly, according to the fundamental waveguide theory [16], the zero-order modified Bessel function can be approximately simplified as:

$$K_0\left(\frac{\Lambda W}{a}\right) = \frac{\pi a}{2W\Lambda} \exp\left(-\frac{\Lambda W}{a}\right)$$

(7)

Secondly, for a weak-guide fiber, since the angle between the ray of light and the axis of the fiber is so tiny that the ray of light can be treated as straight propagation. Consequently, the propagation constant can be approximated as:

$$\beta = n_a k = \frac{V}{a\sqrt{2\Delta}}$$

(8)

Thirdly, to calculate conveniently, we propose an approximation of $K_1(x)$ by fitting the curve within a specific range of $W$ from 1 to 2, which is obtained using Eq. (4),
\[ K_i(W) = \sqrt{\frac{3.3}{W}} \exp(-1.1W) \]  \hspace{1cm} (9)

After calculation, the sum of squares due to error (SSE) of Eq. (9) is about \(2.23 \times 10^{-4}\) and the coefficient of determination (R-square) is 0.9999, indicating that the approximation is accurate enough. According to Eqs. (2)–(9), after mathematical derivation, the average crosstalk under the logarithmic coordinate now can be expressed as the sum of three individual formulas:

\[
\{\text{XT}\}_{db} = A + B + C 
\] \hspace{1cm} (10)

where

\[
A = 10\log_{10} \left( \frac{\sqrt{2} \Delta^{1.5} \pi RL}{(3.3 \Lambda)^2} \right) 
\] \hspace{1cm} (11)

\[
B = 10\log_{10} \left( \frac{WU^4}{V^3} \right) 
\] \hspace{1cm} (12)

\[
C = 10\log_{10} \left[ \exp \left( 4.4 - \frac{2\Lambda}{a} \right) W \right] 
\] \hspace{1cm} (13)

Fig. 1. Error estimation between analytical results and simulation results.

Such analytical equation of average XT is helpful to understand the relationship between XT and WS-XT, then guide us to carry out design optimization. It is obviously shown that, A is independent of the operation wavelength, B is only determined by the waveguide structure, while C depends on both the waveguide structure and the core pitch. Therefore, we can analytically evaluate these formulas’ contributions to both XT and WS-XT. In order to testify the approximations and derivations above accurate enough, we compare the average XT calculation results using approximations with that from numerical simulation [4]. The MCF parameters in the numerical calculations include core radius \(a\) of 3.8\(\mu\)m, core pitch \(\Lambda\) of 40\(\mu\)m, fiber length of 1km, relative refractive index difference \(\Delta\) of 0.35\%, bending radius \(R\) of 10cm, and the wavelength ranges from 1525nm to 1625nm. Figure 1 shows the error estimation between two results. Clearly, Eq. (10) is only over-estimated from 0.06dB to 0.24dB within the operation wavelength range, compared with the average XT without approximations. After selecting several reported MCF parameters, we can conclude that Eq.
based on three approximations is accurate enough to analytically investigate the average XT of homogeneous MCF.

3. MCF design optimization

Since formula A has nothing to do with the operation wavelength, it is a constant with respect to the operation wavelength, once the configuration of MCF is fixed. Thus, we focus on the contributions of formulas B and C. When the relative refractive index difference $\Delta$ is 0.35%, core radius is 3.8 $\mu$m, and core pitch $\Lambda$ is 40 $\mu$m, Figs. 2(a) and 2(b) present the wavelength dependence of B and C, respectively. We can clearly find out that the curves are both almost linear within the 100nm wavelength range. Furthermore, the dynamic range of XT contributed by formula B is about 1dB, while that from formula C is more than 10dB. We can conclude that formula C is the dominant factor of the WS-XT. Its wavelength sensitivity is about 10 times than that of formula B. Nevertheless, both B and C are closely related with a certain MCF structure. Next, we begin to investigate MCF parameters’ impact on the two formulas’ wavelength sensitivity so that we can find out an effective method to suppress the WS-XT.

![Fig. 2. Wavelength dependence of formulas B and C, (a) formula B, (b) formula C.](image1)

![Fig. 3. Impacts of core radius $a$ on the WS-XT of formulas B and C, (a) formula B, (b) formula C.](image2)

First, we explore the effect of core radius. The core radius is varied from 3.5 $\mu$m to 4.4 $\mu$m, meanwhile the relative refractive index difference $\Delta$ is 0.35% and the core pitch is 40 $\mu$m. Figure 3 depicts the variation range of XT from formula B and C. We can see that the WS-XT of B is increasing with the growth of core radius, while that of C is decreasing with the growth of core radius. Nevertheless, neither slope of XT is sensitive to the core radius.
variation. Next, the relative refractive index difference $\Delta$ is changed from 0.3% to 0.45% with core radius $a$ of 3.8$\mu$m and core pitch $\Lambda$ of 40$\mu$m. As shown in Fig. 4, it is clearly observed that the WS-XT of B and C are both increasing with the growth of relative refractive index difference $\Delta$. Because the WS-XT of C is 10 times larger than that of B, the dynamic range of WS-XT contributed by formula C is larger. Besides, different from formula B, not only is formula C determined by the core waveguide structure, but also by the cores distribution, namely, core pitch $\Lambda$. When the core pitch $\Lambda$ is varied from 35$\mu$m to 44$\mu$m, as shown in Fig. 5, we can see that the XT is reduced while the WS-XT becomes sharp. Furthermore, the curves above are all extremely fitted well with the sum of squares due to error (SSE) less than $10^{-4}$.

![Fig. 4. Impacts of relative refractive index difference $\Delta$ on the WS-XT of formulas B and C, (a) formula B, (b) formula C.](image)

![Fig. 5. Impacts of core pitch $\Lambda$ on the WS-XT of formula C.](image)

After analytical investigations, we can conclude that increasing core radius and decreasing relative refractive index difference and core pitch can suppress the WS-XT more or less. Nevertheless, by increasing the core radius, the reduction of WS-XT of C is partially canceled out by the growth of WS-XT of B. With small relative refractive index difference, the bending loss is severely worsen. Hence, reducing the core pitch is the most effective and realistic solution. However, the suppression of the WS-XT by decreasing the core pitch is also contradictory to the average XT suppression. Therefore, we believe there is a balance between the two cases. Taking the quadrature phase shift keying (QPSK) signal as an example, for a 0.5dB crosstalk penalty, it shows a tolerance of crosstalk about $-20$dB [17]. In order to suppress the crosstalk at 1550nm less than $-20$dB, we can obtain a range of core pitch during the MCF design. Then, we need to optimize the WS-XT as flat as possible, in order to achieve the maximum crosstalk at 1625nm no more than $-20$dB. Thus, we can obtain
another range of core pitch. After comparing two conditions of core pitch, we carry out a balance act to obtain specific value of core pitch finally. It is worthwhile to mention that those conclusions of MCF structural parameters’ effects on the WS-XT can also apply to the heterogeneous MCF and MCF with trench-assisted structure after numerical verification, though the coupling coefficient is too complex to obtain an analytical equation as Eq. (10).

4. Experimental characterization and discussions

According to our theoretical investigation, we believe the reduction of the core pitch is feasible to achieve low WS-XT of homogenous MCF. Thus, we fabricate two kinds of homogeneous MCF to testify this conclusion. The structures of two MCFs are the same, except the core pitch. The two core pitches are 35μm and 42μm, respectively. The sectional view of MCF and schematic experimental characterization setup are shown in Figs. 6(a) and 6(b), respectively. A 100m MCF, which is used to verify the theoretical conclusion because of the crosstalk’s linear dependence on the length, is wound around the coiler. One SMF is spliced to the inner core of the MCF by fiber fusion machine, while the other SMF is offset spliced to one outer core with the help of the fiber geometry system (Photon Kinetics 2200), which employs the launching light and imaging devices to realize offset alignment. Then, the CW light generated by a tunable laser source, whose wavelength ranges from 1528nm to 1563nm, is injected into the inner core and then output from one designated outer core, whose power is detected by the optical spectrum analyzer (AQ6370C). Then the offset spliced SMF is replaced by another SMF spliced to the inner core of the MCF whose power is detected by the same OSA. Finally, the crosstalk is obtained by a ratio of output power of designated outer core with that of inner core.

The experimental result of WS-XT is shown in Fig. 7. Each point represents the average value of nearly 100 times measurements and error bars indicate the maximum and minimum values of the measurements. We can obviously observe that the XT is increasing along with the operation wavelength. Noticeably the WS-XT of the 35μm core pitch MCF is about 0.07dB/nm, which is almost 0.05dB/nm less than that of 42μm core pitch MCF. According to the parameters employed in the experiments, the calculated results by the formulas above are 0.08dB/nm and 0.12dB/nm. This phenomenon is interesting, indicating that although the XT is degraded with small core pitch, the XT becomes less sensitive to the operation wavelength, because the mode pattern of individual MCF core is closely related to the operation wavelength. When the core pitch is small, the mode overlapping is so severe in the narrow region between cores that the crosstalk under different operation wavelength cannot be distinguished. However, with the increase of core pitch, the region between cores is expanding and the mode overlapping is weakened. Hence, the crosstalk at the longer wavelength is prominent due to the larger mode effective area, compared with that in the shorter wavelength. Thus, the operation wavelength dependent crosstalk becomes obvious on the condition of large core pitch. Consequently, the corresponding WS-XT has larger value.
5. Conclusion

We have proposed an analytical approach to evaluate the impacts of structural parameters of homogeneous MCF on both the WS-XT and XT, in order to support future SDM fiber optical transmission together with DWDM technique. We find that there exists a performance trade-off between the crosstalk mitigation and the wavelength dependent sensitivity suppression. After experimental characterization, such tradeoff during MCF design is verified. Especially, the core pitch plays a significant but contradictory role in suppression of both the WS-XT and XT.

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