Rayleigh Backscattering in Few-Mode Optical Fibers

Zhen Wang,1,2 Hao Wu,1,2 Xiaolong Hu,1,2,* Ningbo Zhao,1,2 Zhiqun Yang,1,2 Fengze Tan,1,2 Jian Zhao,1,2 Qi Mo,3 and Guifang Li1,2,4

1School of Precision Instrument and Optoelectronic Engineering, Tianjin University, Tianjin 300072, China
2Key Laboratory of Optoelectronic Information Science and Technology, Ministry of Education, Tianjin 300072, China
3Wuhan Research Institute of Posts and Telecommunications, Wuhan 430074, China
4CREOL, The College of Optics & Photonics, University of Central Florida, Orlando, FL 32816, USA
*Author e-mail address: xiaolonghu@tju.edu.cn

Abstract: We measure inter-modal Rayleigh backscattering in few-mode optical fibers and compare the experimental results with simulation results obtained from newly-developed analytical formulae. Excellent agreement between theory and experiment allows investigation of mode-coupling dynamics using OTDR.

OCIS codes: (290.5870) Scattering, Rayleigh; (120.4825) Optical time domain reflectometry; (060.4230) Multiplexing

1. Introduction

Mode-division multiplexing (MDM) [1] has recently attracted tremendous research interest because it, together with multiplexing technologies in other dimensions, is further enhancing the communication capacity in optical fibers. Research on optical components [2] and communication systems [3] for MDM is progressing rapidly. In particular, optical time-domain reflectometry (OTDR) has been successfully used to probe mode coupling in few-mode fibers [4]. OTDR measures reflection and Rayleigh-backscattering signals to remotely characterize the optical losses along fibers. As a mature technology for single-mode fibers, the associated theories have been well established. However, as a tool for emerging MDM systems, the fundamental process of OTDR — Rayleigh backscattering in few-mode optical fibers — have not been systematically studied. What is particularly important is that in few-mode fibers the Rayleigh backscattering excited by one forward-guiding mode can be back-coupled not only to the corresponding backward-guiding mode, but also to other backward-guiding modes. This coupling effect is the key difference with the single-mode case that we can not ignore.

We establish the theory of Rayleigh backscattering in few-mode fibers. Firstly, we set up general equations quantifying local and overall capture fractions and the power of Rayleigh backscattering; second, we derived analytical formulae of capture fractions, under approximations. We further justified the validity of the approximations by comparing the results with and without using them. Finally, we performed OTDR measurement in a three-mode optical fiber and compared the experimental and theoretical results.

2. Theory

We considered the Rayleigh backscattering in a three-mode fiber, containing LP01, LP11a, and LP11b guiding modes. The theory can be easily extended to handle more guiding modes. In this work we didn’t take polarization into account and treated the Rayleigh scattering process as being incoherent. The theory therefore is a scalar theory that can be used for incoherent OTDR in few-mode fibers. The power of Rayleigh backscattering in backward-guiding mode \( j \) \((j = \text{LP}_{01-}, \text{LP}_{11a-}, \text{LP}_{11b-})\), excited by forward-guiding mode \( i \) \((i = \text{LP}_{01+}, \text{LP}_{11a+}, \text{LP}_{11b+})\), can be generally written as

\[
P_{\text{BS}}(z) = \frac{v_{gi}v_{gj}}{v_{gi} + v_{gj}} P(0) \Delta T \alpha_{i}(z)B_{ij}(z)e^{-(\alpha_{i} + \alpha_{j})z},
\]

where \( P_{\text{BS}} \) is the power of Rayleigh scattering in mode \( j \), \( z \) is the direction of forward propagation, \( v_{gi} \) and \( v_{gj} \) are the group velocities of modes \( i \) and \( j \), respectively, \( P(0) \) is the optical power of the pulse launched into the fiber at the front facet, \( \Delta T \) is the width of the pulse, \( \alpha_{i} \) is the Rayleigh-scattering-loss coefficient of mode \( i \), \( B_{ij}(z) \) is the overall capture fraction, \( \alpha_{i} \) and \( \alpha_{j} \) are the loss coefficients of modes \( i \) and \( j \), respectively.

Rayleigh scattering excited by mode \( i \) can be back-coupled to backward-guiding mode \( j \) because the scattered mode and mode \( j \) are not orthogonal; overall capture fraction, \( B_{ij}(z) \), quantifies the ratio of the power back-coupled to mode...
j over the incident power in mode i. Similar to the treatment in Reference [5], the field of Rayleigh scattering was modeled as the field radiated by a dipole: \( \psi_j(r, \theta, \phi) = \psi_0 e^{-jkr - kR_\theta \sin \theta \cos (\phi - \phi_0)} (1 - \sin^2 \theta \cos^2 \phi)^{\frac{1}{2}} \), where \( \psi_0 \) is the field amplitude, \( k \) is the wave vector, \( n \) is the average refractive index of the fiber, \( a \) is the radius of the fiber core, and \( R_\theta \) is the distance between the dipole and the central axis of the fiber. Fig. 1 (a) presents the coordinate system. At a specific point \((R_\theta, \phi_0)\) at a cross section of the fiber, the local capture fraction, \( b_j \), can be calculated by the overlap integral of the far field of mode \( j \) and the far field of the dipole:

\[
b_j(R_\theta, \phi_0) = \frac{1}{2} \frac{1}{2\pi} \frac{1}{2\pi} \left| \int \psi_{fj} \psi_j d\Omega \right|^2.
\]  

(2)

where the far field \( \psi_{fj} \) was obtained from the near field distribution, \( \psi_{nj} \), using Fraunhofer diffraction formula:

\[
\psi_{fj}(r, \theta, \phi) = \frac{j\sqrt{2}}{k} e^{-jkr} \int_0^\infty \int_0^{2\pi} \psi_{nj}(R, \phi_0) \exp\left[jk R \sin \theta \cos (\phi - \phi_0)\right] d\phi_0 R dR.
\]

Using the following approximations and relations: (i) \( 1 - \sin^2 \theta \cos^2 \phi \approx 1 \), (ii) \( \sin \theta \approx \theta \), and (iii) Hankel transforms, Eq. (2) was simplified to

\[
b_j(R_\theta, \phi_0) = \frac{3\pi}{2} \frac{1}{(kan)^2} \left| \int_0^\infty \int_0^{2\pi} \psi_{fj}^2(R, \phi_0) d\phi_0 dR \right|^2.
\]  

(3)

The overall capture fraction, \( B_{ij} \), was \( b_j \) averaged over the intensity distribution of mode \( i \):

\[
B_{ij} = \frac{3\pi}{2} \frac{1}{(kan)^2} \int_0^\infty \int_0^{2\pi} \psi_j^2(R, \phi) \psi_i^2(R, \phi) d\phi R dR.
\]  

(4)

Eq. (2) and Eq. (3) calculate \( b_j \) and \( B_{ij} \), respectively, using the near field distribution of the fiber modes.

Figure 1 (b) - (e) present theoretical capture fractions. Fig. 1 (b), (c), and (d) present local capture fractions, \( b_j \), for LP01, LP11a, and LP11b excitations, respectively, calculated using Eq. (2) without approximations. The distribution of \( b_j \) closely mimics the intensity distribution of mode \( j \). The similarity between the distributions of \( b_j \) and intensity of mode \( j \) can also be clearly seen in Eq. (3) that uses approximations. We calculated \( b_j \) using Eq. (3) as well and found that the maximum relative difference between the results with and without approximations were 6%, justifying the validity of approximations. Fig. 1 (e) presents overall capture fractions, \( B_{ij} \), as a function of normalized frequency, \( V \). The dashed line shows the cutoff frequency of LP11a and LP11b modes, \( V = 2.408 \). The degeneracy of \( B \) is noted.

3. Experiment

We measured Rayleigh backscattering in a three-mode fiber using the experimental setup shown in Fig. 2 (a). A commercial OTDR (YOKOGAWA AQ7283) was used to launch an optical pulse at the wavelength of 1550 nm, with a pulse width of \( \Delta T = 100 \) ns and peak power of \( P_\text{in} = 0.5 \) mW, into a home-built mode-multiplexing/de-multiplexing coupler and then into a three-mode optical fiber (\( n_1 = 1.450; n_2 = 1.443 \); numerical aperture=0.135). The single-pass insertion losses of the mode coupler were 7.33 dB, 3.49 dB, 8.33 dB for LP01, LP11a, and LP11b channels, respectively.
The coupling losses from free space to the three-mode fiber were 1.25 dB, 2.95 dB, 2.46 dB for LP$_{01}$, LP$_{11a}$, and LP$_{11b}$ channels, respectively. The reflected light and Rayleigh backscattering in these three modes were de-multiplexed by the mode coupler and then sent back to the OTDR through circulators. Fig. 2 (a) shows the configuration that the excitation is in LP$_{01}$ mode and the signal collected is in LP$_{11a}$ mode. We manually re-configured the fiber connections for other combinations of excitations and collection-channels.

Fig. 2: Measurement of Rayleigh backscattering in a three-mode optical fiber. (a) Experimental setup: a commercial optical time domain reflectometer was used for excitation and detection; a Laser pulse at the wavelength of 1550 nm, with 100 ns width and 0.5 mW peak power, were launched into the home-built mode multiplexing/de-multiplexing coupler and then into the three-mode fiber. Reflected light and Rayleigh backscattering were de-multiplexed by the mode-coupler and one-by-one sent back to the OTDR through circulators. OTDR: optical time domain reflectometer; C: circulator; L: Lens; BS: beam splitter; M: mirror; SMF: single-mode fiber; FMF: few-mode fiber; PP1: phase plate 1 in LP$_{11a}$ channel; PP2: phase plate 2 in LP$_{11b}$ channel. (b), (c) and (d) present measured Rayleigh backscattering for LP$_{01}$+, LP$_{11a}$+, and LP$_{11b}$+ excitation, respectively. The theoretical results are shown in dashed lines.

Figure 2 (b), (c), and (d) present the results with LP$_{01}$, LP$_{11a}$, and LP$_{11b}$ excitations, respectively. The reflection from the front facet of the fiber generated a dead zone approximately from 0 to 1.5 km. We note that using photonic lanterns as mode couplers can reduce the reflection and the associated dead zone; or using active switches [4] can eliminate them. In our current experiment we used the data outside the dead zone from 1.5 km to 3 km for analysis to minimize the experimental error. We also presented the theoretical results calculated using Eq. (1) with no free parameters. In our calculation the following parameters were used: $\alpha_s = 0.17$ dB; $\alpha_i = \alpha_j = 0.23$ dB; $v_g \approx v_g \approx 2.069 \times 10^8$ m/s for all relevant modes. The maximum difference between the fitted lines of the experimental data ranging from 1.5 km to 3 km and the theoretical lines was 1.5 dB.

4. Conclusion

We have presented the theory of Rayleigh backscattering in few-mode fibers and have compared the theoretical results with experiment. The theory quantifies capture fractions and the power of Rayleigh backscattering in each mode. Our results clearly show that even in absence of coupling between the guiding modes in few-mode fibers, an excitation in certain forward-guiding mode can generate Rayleigh backscattering in other backward-guiding modes. The results presented in this paper will be useful for interpreting mode-coupling dynamics in few-mode fibers using multi-mode OTDR. Understanding of mode-coupling dynamics is crucial to optimizing performance of MDM systems.

Acknowledgement

This work was supported by National Basic Research Program of China (973) (No. 2014CB340104/1) and National Science Foundation China (project number: 61377076).

References