Optics Communications 346 (2015) 15–20

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Mode-dependent characteristics of Rayleigh backscattering in weakly-coupled few-mode fiber

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ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
5 February 2015
Accepted 12 February 2015
Available online 16 February 2015

Key Words:
Fiber characterization
Rayleigh backscattering
Fiber Optics
Mode division multiplexing

ABSTRACT

We theoretically investigate the mode-dependent characteristics of Rayleigh backscattering arising in weakly-coupled few-mode fibers (FMFs). Based on the theory of Lorentz reciprocity and surface wave excitation, we derive a general analytical equation of excitation efficiency and power distribution of Rayleigh backscattering light among backward propagation modes under the condition of impulse response. Thus, we are able to characterize the Rayleigh backscattering of weakly-coupled FMF with arbitrary refractive index profile. As for the weakly-coupled FMF with a step-index profile, the power distribution ratio of individual modes in the Rayleigh backscattering light is mainly determined by the forward propagation mode. In particular, the backscattering mode with the same profile as the forward propagation one has the highest excitation efficiency. The FMF parameters have influence on the total backscattering power, but little effect on the mode power distribution ratio.

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1. Introduction

Recently, the prospect of capacity crunch in single mode fiber (SMF) has stimulated worldwide interests in mode division multiplexing (MDM) using few-mode fiber (FMF), together with multi-input multi-output (MIMO) signal processing technique[1, 2]. Rayleigh backscattering (RB) is an important characteristic of FMF to be investigated, though it is rarely discussed in the literature. In the FMF-based EDFA, the RB contributes to the mode dependent gain fluctuations [3]. In Raman amplifiers (RAs), the multiple-path interference noise due to the RB is one of dominant noises [4, 5]. Especially in the FMF-based RAs, the RB induces strong multiple-path interference noise, resulting in the noise figure (NF) difference among propagation modes [6]. Meanwhile, as for the bidirectional transmission in passive optical network (PON), the RB is regarded as one of the dominant noise sources [7]. The eye diagram of the upstream mode channel is not as clear as that of the downstream mode channel partially due to the impact of RB when MDM is used, limiting the reaching distance [8]. Furthermore, the mode distribution of the RB light in the FMF has significant influence on the demonstration of measuring the mode coupling property along the FMF using optical time-domain reflectometry (OTDR) [9]. Without taking into consideration the RB light power distribution among the fiber modes, the measured mode coupling coefficient may deviate from the precise value. Generally, the RB in optical fibers comes from the fiber structural fluctuations and has been well investigated in SMF [10-12]. In order to calculate the amplitude of backscattering light in the SMF, the field distribution is usually approximated with a Gaussian function [10, 11]. Due to the existence of few modes, such approximation becomes invalid and the conclusions of SMF cannot be applied to the FMF. Some researchers have explored the RB in multi-mode fibers (MMFs) [13, 14]. The mode distribution of backscattering light in MMF is experimentally found to be determined by the forward propagation mode [13]. Then, the RB in MMF is theoretically investigated with an assumption of mode continuum [14]. In a strongly coupled MMF, when the linewidth of optical source is wide enough, the propagation constants are so close as to be treated as continuum among degenerate mode groups. Obviously, such condition becomes invalid for the weakly-coupled FMF, whose effective index difference between arbitrary linearly polarized (LP) modes is larger than 0.5×10^{-3} [15]. Currently, weakly coupled FMF is commonly used in MDM transmission system, due to the benefit of receiver complexity reduction [16]. Thus, it is necessary to analyze the mode-dependent characteristics of RB arising in weakly-coupled FMF.

To the best of our knowledge, there exists no theoretical investigation of mode-dependent characteristics of RB in weakly-coupled FMF. In this paper, based on the theory of Lorentz reciprocity and surface wave excitation [17], we obtain a theoretical expression of RB light under the condition of impulse response. With numerical calculations, we find that the total Rayleigh

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http://dx.doi.org/10.1016/j.optcom.2015.02.027
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backscattering power (TRBP) and the corresponding mode power distribution ratio (MPDR) are determined by the forward propagation mode. The FMF parameters have influence on the TRBP but have little effect on the MPDR. The rest of the paper is organized as follows. Section 2 describes the theoretical model to investigate the mode-dependent characteristics of RB in weakly-coupled FMFs. Section 3 discuss the variation of TRBP and MPDR with respect to the FMF parameter with a step-index profile. The calculation results agree well with the RB characters of SMF, when the FMF parameters are changed to only support the fundamental mode. The main conclusions are summarized in section 4.

2. Theoretical model

The RB light occurs due to the inhomogeneities $\Delta\chi(x,y,z)$ of the local electric susceptibility during the FMF drawing. The small scale perturbation of permittivity $\Delta\varepsilon$ at the location (x,y,z) acts as a dipole to scatter the input light. The model of equivalent dipole and surface wave excitation is widely used in the RB investigation and is suitable for any types of optical fibers [10, 11]. Thus, we start to investigate the RB of weakly-guided weakly-coupled FMF with the same method. The generated dipole current $\mathbf{J}$ can be described as,

$$\mathbf{J} = i\omega\Delta\varepsilon(x, y, z)\mathbf{E_{in}} = i\omega\varepsilon_0\Delta\chi(x, y, z)\mathbf{E_{in}}, \tag{1}$$

where ω is the angular frequency, $\mathbf{E_{in}}$ is the incident electric field. We omit the time harmonic term $\exp(i\omega t)$ for the ease of discussion. Taking the light scattering from a length element dz located at into account, we can derive the field amplitudes a_{mn}^{-} of the modes LP_{mn} excited by the equivalent dipole according to the Lorentz reciprocity theorem.

$$a_{mn}^{-} = \frac{-\int_{V_S} J{\cdot}E_{mn}dV}{2\int_S E_{mn}(x, y)\times H_{mn}(x, y)dS_1} \tag{2}$$

$E_{mn}(x,y)$ and $H_{mn}(x,y)$ are the transverse distributions of the normalized electric and magnetic field in the cross section S, respectively, and V_S is the volume, dS_1 is the surface element, dV is the volume element of dS_1dz. Assuming dz is small enough that the amplitude of the forward mode can be regarded as a constant, we can obtain the amplitude of backscattering light at LP_{mn} mode.

$$a_{mn}^{-}(z) = -\frac{\int_S i\omega\Delta\varepsilon(x, y, z)E_{in}(x, y, z){\cdot}E_{mn}(x, y)dS_1dz}{2\int_S E_{mn}(x, y)\times H_{mn}(x, y)dS_1} \tag{3}$$

Eq. (3) can be further simplified as

$$a_{mn}^{-}(z) = -(1/c)i\omega n\sqrt{P_{lp}}\cdot\int_S n_r(x, y, z)A_{lp}^{-1/2}e_{lp}(x, y) \times \exp\left(-\alpha_{lp}z/2\right){\cdot}A_{mn}^{-1/2}e_{mn}(x, y)dS_1 \tag{4}$$

where $n_r(x,y,z)$ is the refractive-index fluctuation, P_{lp} is the initial power of the forward light at mode LP_{lp}, $\alpha_{lp}$is the corresponding attenuation coefficient, $A_{lp}^{-1/2}$and $A_{mn}^{-1/2}$ are the normalized amplitudes as shown in Eq. (5), $e_{mn}(x,y)$ and $e_{lp}(x,y)$ are the transverse distributions of the electric field, μ and ε are the permeability and permittivity, respectively.

$$A_{lp}^{-1/2} = \left[\int_0^\infty\int_0^\infty \left|e_{lp}(x, y)\right|^2/\sqrt{\mu/\varepsilon}\,dxdy\right]^{-1/2} \tag{5a}$$

$$A_{mn}^{-1/2} = \left[\int_0^\infty\int_0^\infty \left|e_{mn}(x, y)\right|^2/\sqrt{\mu/\varepsilon}\,dxdy\right]^{-1/2} \tag{5b}$$

Since the RB is an intrinsic property of fiber, the input pulse profile does not change the scattering characteristics of FMFs. For the ease of discussion, we start our derivation on the condition of impulse response [18]. The total power of the scattered light in LP_{mn} mode can be the integration of Eq. (4) in the longitudinal direction, as shown in Fig. 1. Because the scattering elements are random, the backscattering power is given by an ensemble average.

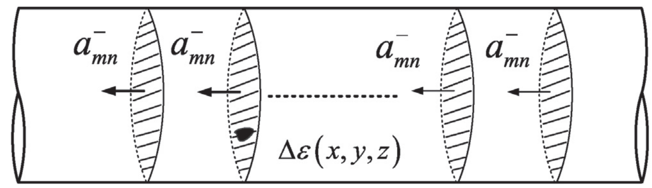

Fig. 1. Schematic model of the infinite narrow pulse scatting in a FMF.

$$\begin{aligned} P_{Slp-mn} &= \left\langle \left|E_{Smn}\right|^2 \right\rangle \\ &= \left\langle \left| \int_0^L \int_S E_{Smn}(x, y, z)dSdz \right|^2 \right\rangle \\ &= \left\langle \left[\int_0^L a_{mn}^{-}(z)dz\right]\cdot\left[\int_0^L a_{mn}^{-}(z)dz\right]^* \right\rangle \end{aligned} \tag{6}$$

where E_{Smn} is the electric field of the backscattering light in LP_{mn} mode and $P_{Slp\text{-}mn}$ is its power, when the forward propagation mode is LP_{lp} mode. Here, we apply the Gaussian distribution model to the refractive-index fluctuation, $n_r(x, y, z)$[11]. For the strongly-coupled FMF, the amplitude items inside the integration components should include all the supported LP modes and corresponding coupling interaction for the strongly-coupled FMF and no theoretical expression can be obtained. Thus we deal with the following derivation based on the weakly-coupled FMFs, neglecting the effect of mode coupling when the backscattering light propagates. And we reasonably neglected the coefficient $\sqrt{\mu/\varepsilon}$ for both the forward and the backward field, because we only care about the RB power relative to the input impulse power. It is well known that the electric field in FMF can be expressed as the product of radial part and angular part as,

$$E_{mn}(x, y) = E_{mn}(r, \theta) = \varphi_{mn}(r)\cos(m\theta) \tag{7}$$

where (r, θ) is the polar coordinate, $\varphi_{mn}(r)$ is the radial distribution of transverse electric field. Substituting Eq. (4) and Eq. (7) into Eq. (6), we obtain the backscattering power in LP_{mn} mode as described in Eq. (8) after mathematical derivation

$$P_{Slp-mn} = CF(L)\int_0^\infty\int_0^\infty f(r_1, r_2){\cdot}Q(r_1, r_2)dr_1dr_2 \tag{8}$$

where the corresponding symbols and functions are defined as follows

$$f(r_1, r_2) = r_1r_2\cdot\varphi_{lp}(r_1)\varphi_{mn}(r_1)\varphi_{lp}(r_2) \times \varphi_{mn}(r_2) \exp\left[-\left(r_1^2 + r_2^2\right)/l_c^2\right] \tag{9}$$

$$C = \left(n^2\omega^2P_{lp}/c^2\right)\left\langle n_r^2\right\rangle A_{lp}^{-1}A_{mn}^{-1} \tag{10}$$

Table 1
Parameters of the Few-Mode Fibers

Item	Core Radius [μm]	n_cladding	Δn [$\times 10^{-3}$]	λ [μm]	l_c	$\langle n_r^2\rangle$ [$\times 10^{-5}$]
1	8	1.45601	6.3∼8.7	1.55	10	5.2
2	7.4∼8.9	1.45601	7	1.55	10	5.2

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