Optics Communications 413 (2018) 224–229

Contents lists available at ScienceDirect

Optics Communications

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

Artificially controlled backscattering in single mode fibers based on femtosecond laser fabricated reflectors

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ARTICLE INFO

Keywords:
Rayleigh backscattering
Femtosecond lasers
Distributed feedback

ABSTRACT

A novel method to artificially control the backscattering of the single-mode fiber (SMF) is proposed and investigated for the first time. This method can help to fabricate a high backscattering fiber (HBSF), such as by fabricating reflectors in every one meter interval of an SMF based on the exposure of the femtosecond laser beam. The artificially controlled backscattering (ACBS) can be much higher than the natural Rayleigh backscattering (RB) of the SMF. The RB power and ACBS power in the unit length fiber are derived according to the theory of the RBS. The total relative power and the relative back power reflected in the unit length of the HBSF have been simulated and presented. The simulated results show that the HBSF has the characteristics of both low optical attenuation and high backscattering. The relative back power reflected in the unit length of the HBSF is 25dB larger than the RB power of the SMF when the refractive index modulation quantity of the reflectors is 0.009. Some preliminary experiments also indicate that the method fabricating reflectors to increase the backscattering power of the SMF is practical and promising.

1. Introduction

The theoretical analysis of the Rayleigh backscattering (RBS) in single-mode fiber (SMF) appeared in 1980 [1] and was subsequently verified in experiments [2]. The optical time domain reflectometer (OTDR) based on the RBS mechanism has been widely used to examine loss and imperfections previously [3]. The technique involves launching a light pulse into the fiber and examining the temporal behavior of the signal that is recaptured by the fiber in the return direction [4]. Along with the rapid development of the laser technology, the phase-sensitive OTDR based on the RBS mechanism has become a powerful technique that allows fully distributed vibration sensing along the entire sensing fiber. The phase-sensitive OTDR has advantages of fast response, high sensitivity and multipoint detection capacity and has been applied in many fields such as intruder detection [5] and structure health monitoring [6]. In recent years, the RBS has also attracted great attention due to applications in random distributed feedback fiber lasers (RDFBFL) [7–9]. However, along with the optical fiber manufacturing technology improves continuously, the RBS that is caused by randomly distributed refractive index inhomogeneity throughout the length of the fiber becomes increasingly weak. Tens of or even hundreds of kilometers of SMF is required to provide enough feedback in RDFBFLs. In order to reduce structural complexity of RDFBFLs, shortening the length of feedback SMF becomes a new research purpose in respect of RDFBFLs. Methods of introducing random refractive index modulation in the SMF have been proposed [10], such as random fiber Bragg grating array [11–13], fiber taper [14], random refractive index modulation by carbon dioxide laser [15]. On the other hand, there has been significant advances in applying femtosecond laser to restructure the fiber to enhance the backscattering of a polymer fiber [16] and form fiber Bragg gratings by means of phase-mask interference [17] or direct fabricating [18], offering strong response without the need for photosensitivity enhancement technique [19].

In this paper, a novel method to artificially control the backscattering of the SMF by using a femtosecond laser is established and simulated theoretically. This method can help to fabricate a high backscattering fiber (HBSF), such as by fabricating reflectors in every one meter interval of an SMF based on the exposure of the femtosecond laser beam. The artificially controlled backscattering (ACBS) can be much higher than the natural RBS of the SMF. The RB power and ACBS power in unit length is derived according to the theory of RBS of the SMF. The total relative power and the relative back power reflected in the unit length of the HBSFs have been simulated and presented. The simulated

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https://doi.org/10.1016/j.optcom.2017.12.054
Received 28 April 2017; Received in revised form 7 December 2017; Accepted 20 December 2017
0030-4018/

results show that the HBSFs have the characteristics of both low optical attenuation and high backscattering. Some preliminary experimental results have also been obtained. The experimental results indicate that the proposed method to increase the backscattering power of the SMF by introducing reflectors based on the exposure of the femtosecond laser beam is practical and promising.

2. Rayleigh backscattering in a single-mode fiber

The Rayleigh Scattering (RS) is the dominant reason of the optical power attenuation for an optical fiber. Light will be scattered toward all directions because of fiber density fluctuations when the light propagates along an optical fiber. For the purpose of present argument, it assumes that the pulse launched into the fiber is a Dirac function of optical power $p(0)$ and vanishingly pulse-width and the RS loss coefficient is equivalent to the loss coefficient of the optical fiber. These assumptions do not affect the results of analysis. The effect of a finite pulse-width w is to limit the distance resolution of measurement to $\delta x = \upsilon_g w/2$ where υ_g is the group velocity in the fiber. For a constant input optical power, varying the pulse-width will not alter the RS signal level.

The pulse power that is propagating in optical fiber is attenuated at a rate α_r and its dependence on position z is thus

$$P(z) = P(0)\exp(-\alpha_r z) \tag{1}$$

where $P(0)$ is incident pulse power, $P(z)$ is the pulse power of apart from incident end z, α_r is the RS loss coefficient. When the pulse propagates a distance element dz situated at z, the pulse power scattered is

$$dp(z) = -\alpha_r p(0)\exp(-\alpha_r z)dz. \tag{2}$$

The total pulse power scattered in the unit length situated at z is

$$p = \frac{dp(z)}{dz} = -\alpha_r p(0)\exp(-\alpha_r z). \tag{3}$$

It defines the capture fraction $B(z)$ as the proportion of which is recaptured by the fiber in the return direction in the total power scattered by the SMF situated at z. Therefore the back power scattered in the unit length situated at z to the launching end is

$$p_B(z) = -\alpha_r B(z)p(0)\exp(-2\alpha_r z). \tag{4}$$

3. Principle of enhancing backscattering

The femtosecond laser beam can induce refractive index change in the fiber core region based on multi-photon absorption [20]. As the fiber is fabricated one reflector situated at z by the femtosecond laser beam, the refractive index of the reflector is larger than the region that is not fabricated. As is shown in Fig. 1, a reflector that is amplified exaggeratedly includes two interfaces of two kinds of different refractive index medium. According to the principle of Fresnel, a portion of the incident light can be reflected and another portion of the incident light is transmitted by the interface. When the light is vertically incident to the interface of two kinds of different refractive index medium, the reflectivity and transmissivity of the single interface are

$$R_1 = \frac{[(n+\Delta n)-n]^2}{[(n+\Delta n)+n]^2} = \frac{\Delta n^2}{(2n+\Delta n)^2} \tag{5}$$

and

$$T_1 = 1 - R_1 = \frac{4n(n+\Delta n)}{(2n+\Delta n)^2} \tag{6}$$

respectively, where n is the refractive index of the fiber core of the SMF, and Δn is the refractive index increment of the reflector that is fabricated by the femtosecond laser. The light incident to the reflector will pass through two interfaces of two kinds of different refractive

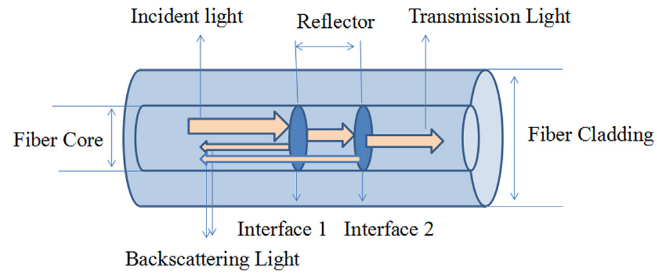

Fig. 1. Illustration of the reflector reflects and transmits the incident light.

index medium. Therefore, the total reflectivity and transmissivity of the reflector are

$$R = \frac{\Delta n^2}{(2n+\Delta n)^2} + \frac{16n^2\Delta n^2(n+\Delta n)^2}{(2n+\Delta n)^6} \tag{7}$$

and

$$T = \frac{16n^2(n+\Delta n)^2}{(2n+\Delta n)^4} \tag{8}$$

respectively. For the fiber with one reflector situated at z fabricated by the femtosecond laser beam, the increment of the back power scattered in the unit length situated at z to the launching end is

$$\Delta p = \mathrm{Rp}(z) = \left[\frac{\Delta n^2}{(2n+\Delta n)^2} + \frac{16n^2\Delta n^2(n+\Delta n)^2}{(2n+\Delta n)^6}\right] p(0)\exp(-2\alpha_r z). \tag{9}$$

For the position from 0 to z_0, the back power scattered in the unit length situated at z to the launching end is

$$p_{B1} = -\alpha_r B(z)p(0)\exp(-2\alpha_r z). \tag{10}$$

The total pulse power scattered in the unit length situated at z_0 to the launching end is

$$p_{Bz_0} = -\alpha_r B(z)\mathrm{p}(0)\exp(-2\alpha_r z_0) + \left[\frac{\Delta n^2}{(2n+\Delta n)^2} + \frac{16n^2\Delta n^2(n+\Delta n)^2}{(2n+\Delta n)^6}\right] p(0)\exp(-2\alpha_r z_0). \tag{11}$$

As the position is larger than z_0, the pulse power scattered in the unit length situated at z to the launching end is

$$p_{B2} = \frac{16n^2(n+\Delta n)^2}{(2n+\Delta n)^4}\alpha_r B(z)p(0)\exp(-2\alpha_r z). \tag{12}$$

4. Characteristics of high backscattering fiber

An HBSF is fabricated with one reflector in every one meter interval of an SMF based on the exposure of the femtosecond laser beam. The equivalent loss coefficient of the HBSF is $\alpha = \alpha_r + \alpha_f$. Where α_f is the equivalent additional loss coefficient introduced by the reflectors. According to the definition of loss coefficient, α_f is

$$\alpha_f = -10\lg\left(\frac{16n^2(n+\Delta n)^2}{(2n+\Delta n)^4}\right). \tag{13}$$

The pulse power propagated in the HBSF is attenuated at a rate α and its dependence on the position z is thus

$$p_f(z) = p(0)\exp\left(-\left(\alpha_r + \alpha_f\right)z\right). \tag{14}$$

As the pulse is propagated in the HBSF, the natural RB power in the unit length situated at z is

$$p_{\alpha r} = \alpha_r p(0)\exp\left(-\left(\alpha_r + \alpha_f\right)z\right). \tag{15}$$

At the same time, the equivalent pulse power reflected by the reflectors in the unit length situated at z is

$$p_{\alpha f} = \alpha_f p(0)\exp\left(-\left(\alpha_r + \alpha_f\right)z\right). \tag{16}$$