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Effect of optical fiber core diameter on Brillouin scattering loss

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Abstract. This paper reports the effect of core diameter of optical fiber cables on stimulated Brillouin scattering loss, which is one of the major loss characteristics of an optical fiber communication system. Analysis of this loss characteristic at three windows of the operating wavelength of a laser has been carried out through a numerical approach. Among different types of optical fiber cables, multi-mode step index silica fiber, multi-mode graded index silica fiber and plastic fibers have been considered for the numerical analysis. The numerical analysis has been performed using MATLAB in this research work. Through the comparative analysis, it has been ascertained that the Brillouin scattering loss is not only affected by the operating wavelength, but also by the core diameter of the different type of the cable. From the investigation of the comparative analysis, it is revealed that Brillouin scattering loss declines with the application of multi-mode graded index silica fiber. However, in the plastic fiber category, plastic step index fiber offers better performance.

Keywords: Brillouin scattering loss, core diameter, operating wavelength, graded index fiber, step index fiber.

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1. Introduction

Information is usually transmitted from one place to another with the help of optical fiber communication system by using optical fiber waveguide. Optical fiber waveguide is composed of core with higher refractive index materials than that of cladding layer used to transmit a light signal over a long distance by using total internal reflection [1, 2]. Optical fiber cables along with their semiconductor optoelectronic components – lasers and photodetectors – have significant contribution in designing fifth generation communication system. Current advancement of optoelectronic technologies not only significantly increases the bandwidth of telecommunication systems but also solves the problems of weak spots in the configuration of next generation wireless networks [3, 4]. However, this communication system suffers from different types of problems, namely: dispersion, attenuation and different kinds of non-linear effects [5].

Among the major problems, dispersion creates the egregious inconvenience for the optical fiber communication system. Dispersion is the effect of pulse spreading of the signal in an optical fiber, which increases with the length of cable. The main reason for the dispersion is the pulse width of the signal in an optical fiber, which depends on the refractive index of the material and wavelength of the carrier. Because of this effect, the signal pulses overlap with each other. Hence, the signal quality at the output end is degraded. This happens for both digital and analog signal transmission through the optical fiber. By describing the nature of group velocities of guided modes in the optical fibers, the creation of dispersion effects can be described. When the optical fiber transmission is in prime operation, then the transmission system uses several types of the digital and analog modulation process. As a result of dispersion, broadening the transmitted light pulses moves forward to the optical receiver through the channel. Dispersion constricts the bandwidth or message transmitting capability of a fiber. In an optical fiber communication system there are three major types of dispersion [6, 7]. These are as follows: 1. Modal dispersion. 2. Material dispersion. 3. Waveguide dispersion.

The modal dispersion takes place in multi-mode optical fiber because the light beams of different modes in multi-mode fiber follow the different paths through the fiber. Therefore, these signals reach the output terminal of the optical fiber channel at different times. For this reason, the entering time of light is the same but the exit time in the output end is different. Hence, light is spread out and this creates the modal dispersion in optical fibers.

Material dispersion arises in the optical fiber because light of various wavelengths travels at different velocities along the fiber even in the same mode. Therefore, their velocity, as well as their refractive index change, which creates material dispersion. The third type of dispersion is waveguide dispersion that depends on the physical form of the waveguide and polarization mode dispersion. This results because of birefringence [8, 9]. Minimization of dispersion effects in the optical fiber communication is the most essential factor, because it creates pulse spreading that causes the output pulses to overlap [4, 10].

Another important phenomenon of optical fiber communication system is the bending loss, which occurs when an optical fiber cable undergoes bending. There are two types of bending losses, namely: (1) micro-bending and (2) macro-bending. The microscopic bending occurs when the core or cladding undergoes slight bends at its surface. The micro-bending loss occurs due to radiation of the evanescent field in the cladding region [11].

The nonlinear effects of optical fiber communication system ensue because of the nonlinear phenomena that occur inside the optical fibers. Among them self-phase modulation (SPM) and four-wave mixing (FWM) can deliver high optical powers in an optical fiber communication system. In SPM, the refractive index of the material gets modified because of the light pulse, and that leads to the modification in the pulse propagation. The pulse intensity changes the refractive index of the optical fiber, and that refractive index changes the velocity, the velocity changes the phase, which is produced by the pulse itself that creates SPM. Another one is FWM, it occurs when multiple light beams propagate through the waveguide. It is the strongest parametric wave, mixing nonlinearities. The nonlinear effects in the optical fiber cable occur either because of intensity dependence of the ratio of the medium or because of inelastic scattering [5]. Several kinds of nonlinear effects arise based on SPM, FWM and cross-phase modulation. The various properties of non-linear effects including their thresholds, management, and applications are also explained in different studies [12, 13].

The optical fibers are classified into two groups according to their modal properties. These are the single-mode fibers and multi-mode ones. The step index profile takes place in single-mode fibers. The step or graded index refers to the distribution of refractive indices within the optical fiber. In the step index fiber, the core has one single uniformly distributed index and its cladding has a lower uniformly distributed index. On the other hand, in the graded index profile the refractive index varies gradually as a function of radial distance from the center of the optical fiber cable. In a step index fiber the core of the fiber is surrounded by the cladding layer. The total internal reflection takes place at the core cladding interface in the step index fiber. In the graded-index fibers, the step by step decrease in the index of refraction occurs. The total internal reflection takes place within the range of fiber grading. The fiber orbit allows light to reflect back to the axis as they extend [8, 10, 14].

Among these three (0.89, 1.3, 1.55 μm) communication windows 1.55 μm offers the lowest attenuation, greater repeater spacing, and higher bit rate. These phenomena made it possible to use coherent optical sources compatible with the standard silicon fibers used in optical fiber communication [8, 10]. Therefore, most of the recent works on light sources and detectors have been concentrated on semiconductor optical sources and detectors. These devices with Group-III-V compounds in active layers have been studied extensively and used almost exclusively for the present light-wave communication systems in these wavelength regions [4, 15]. Efforts have been made to enhance the laser and photo-detector performances. However, the losses due to Brillouin scattering increase at the rate of 2 with the increase of wavelength [16]. It has been reported that to reduce stimulated Brillouin scattering (SBS) loss of optical fibers, electronic filters are applied widely [17]. Hence, to utilize the enormously potential bandwidth of optical fiber, the prospect of minimizing the loss is still required [18]. Therefore, this research work has been devoted to analyze the feasibility of reducing the application of electronic filter by analyzing the effect of optical fiber core diameter on SBS, which may lead to a reduction in optical fiber diameter to some extent.

2. Mathematical modeling

2.1. Stimulated Brillouin scattering process

It has been reported that several kinds of beneficial properties of optical fiber have been utilized for applications. Among these features, phase conjugation, optical limiting, pulse compression, and beam combination are significant [19]. The uses of these technologies are increasing rapidly, and they are incessantly promoted in the field of optoelectronic engineering. SBS and stimulated Raman scattering (SRS) are the third-order nonlinear optical processes. Both SRS and SBS require high radiation. SBS emanates from the excited medium of an acoustic wave [5, 20].

It expresses itself by making reverse or onward propagating Stokes wave which shifts from the frequency of the incident pump wave by a volume, which is defined by the frequency of phonon. Both stimulated and spontaneous operation of Brillouin scattering involves pump photon [21, 22]. The frequency of pump photon is denoted by ω_p. It generates acoustic phonon having a frequency of ω_n and the downshifting (brown color in Fig. 1) Stokes photon at a frequency $\omega_S = \omega_p - \omega_n$.

The instant is anti-Stokes Brillouin scattering, which absorbs phonon in an excited medium. It creates up-shifting (denoted by blue in Fig. 1) anti-Stokes photon that has a frequency of $\omega_{aS} = \omega_p - \omega_n$ and also acoustic phonon (ω_n) are created, which is shown in the energy-level diagram in Fig. 1.

For the Stokes and anti-Stokes Brillouin scattering, the energy and velocity conservation requirements are mentioned below.

Stokes: $\omega_S = \omega_p - \omega_\Omega$, $K_S = K_p - K_\Omega$,

anti-Stokes: $\omega_{aS} = \omega_p + \omega_\Omega$, $K_{aS} = K_p + K_\Omega$,

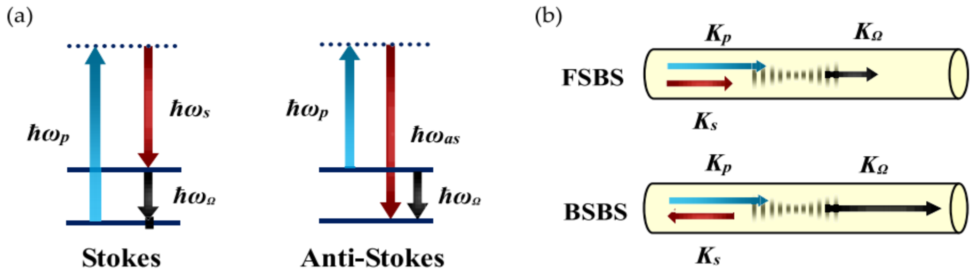


Fig. 1. Principle of Brillouin scattering processes: (a) energy-level diagram of Brillouin scattering processes (Stokes and anti-Stokes), (b) phase-matching diagrams for forward and backward SBS.

where K_p is the pump wave vectors, K_S – Stokes wave vectors, K_{aS} – anti-Stokes wave vectors, and K_Ω – phonon wave vectors.

Here, $K_p = \omega_p n p/c$ and $K_\Omega = \omega_\Omega/v$; where c – speed of light and v – acoustic velocity in the medium.

When stimulated Brillouin scattering being in operation, then $\omega_\Omega << \omega_p$, ω_S, ω_{aS}. Now we can say that $\omega_p = \omega_S$, $K_p = K_S$.

From this consideration, the new formula will be $K_\Omega = 2K_p \sin(\theta/2)$, where θ is the angle between pump and Stokes wave vectors.

For SBS, the frequency shift is the highest value in the reverse direction which reduces to zero toward the forward direction, which makes SBS mainly a reverse process. For the SBS loss has a significance above a threshold, it is given by the following equation [10]:

$$P_R = 0.044 d^2 \lambda^2 \alpha d B, \tag{1}$$

where P_R is the SBS optical threshold power level (W), d – fiber core diameter (μm), λ – operating wavelength (μm), α – Fiber loss (dB/km).

2.2. Process flow chart of numerical analysis of stimulated Brillouin scattering

This subsection presents the detail description of the process flow chart and algorithm for obtaining the results by using MATLAB. The multi-mode step index silica fiber, multi-mode graded index silica fiber and plastic fibers have been used for the research work. For the analysis, core diameters of the fibers considered in this research are presented in Table 1.

In order to accomplish this research work, the following steps have been performed:

Table 1. Range of core diameter of four types of optical fiber cables [10].

Type of fibers	Diameter of fibers (μm)
multi-mode step index silica fiber	140 – 400
multi-mode graded index silica fiber	125 – 150
step index plastic fiber	300 – 1400
graded index plastic fiber	125 – 150

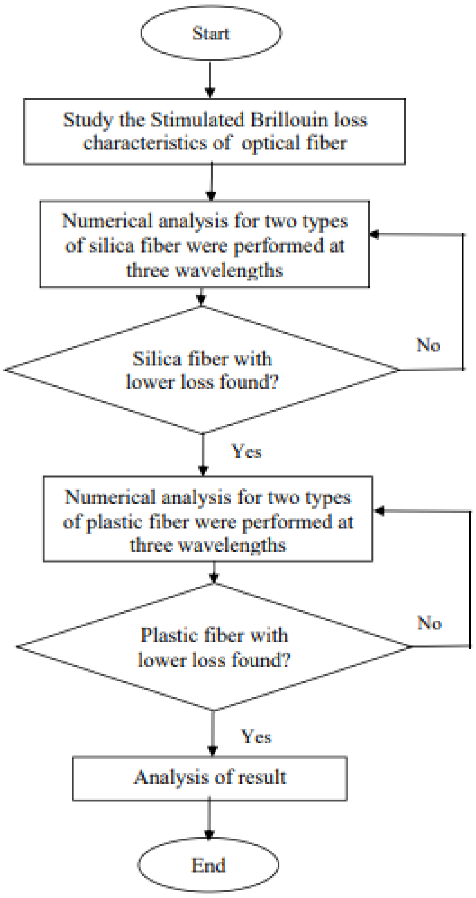
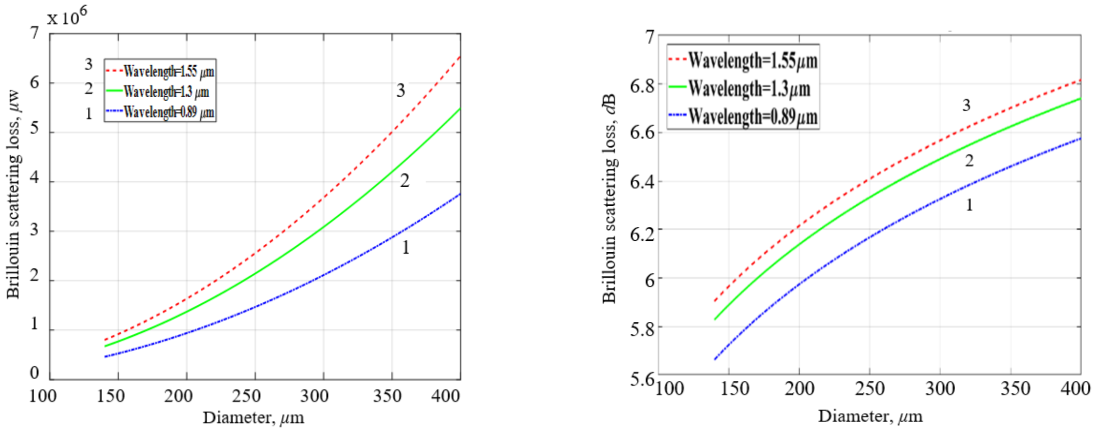


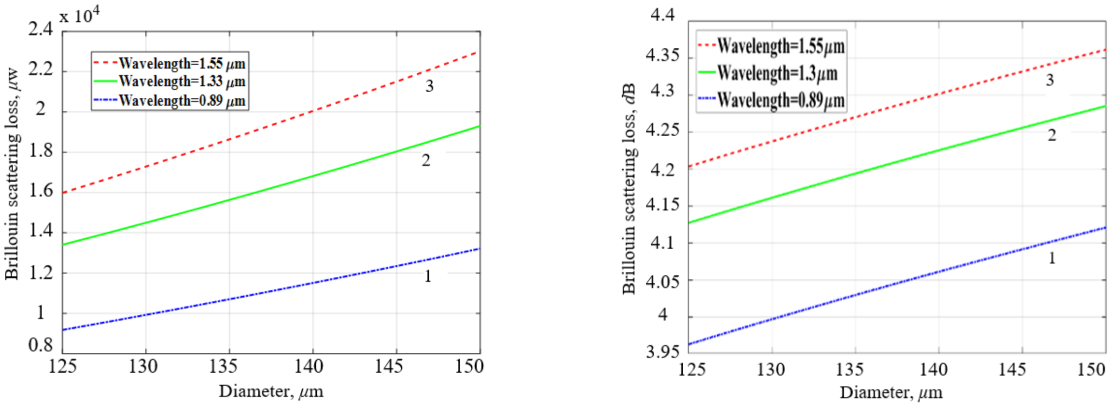
Fig. 2. Process flow chart for numerical analysis SBS loss.

1. An extensive literature review has been carried out on SBS loss. From the literature review a lot of information about the loss characteristics and four types of fiber have been collected.
2. The parameters required for investigation of these loss characteristics were identified. When investigating, it was found that diameter dependence of SBS loss has not been investigated yet. Therefore, this research was aimed at determining the effect of diameter of optical fiber core on SBS loss. MATLAB software has been used to analyze the numerical calculations.
3. The obtained results were then analyzed, and findings were concluded in Sections 4 and 5, respectively.



(a) (b)

Fig. 3. Diameter dependence of multi-mode step index silica fiber for three windows of optical fiber communication system. Blue (1), green (2) and red (3) lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively.



(a) (b)

Fig. 4. Diameter dependence of multi-mode graded index silica fiber for three windows of optical fiber communication system. Blue (1), green (2) and red (3) lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively.

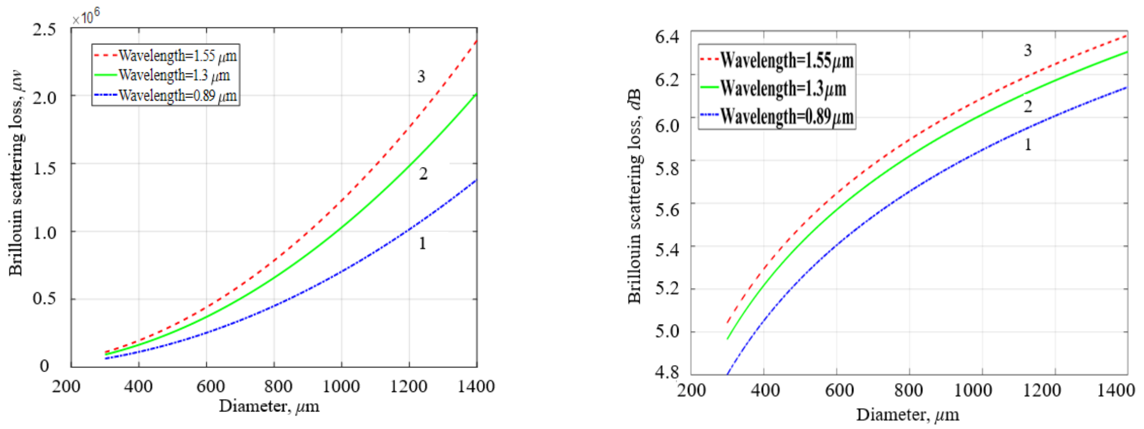
3. Numerical results

This section presents the detail description of the obtained results through the comparative analysis of the effect of optical fiber cable diameter on the SBS loss for three optical fiber windows. The variation of SBS loss has been investigated numerically using MATLAB. The types of cables used in this analysis were as follows: multi-mode step index silica fiber, multi-mode graded index silica fiber and plastic fibers. These characteristics have been presented in Figs 3 to 6.

Fig. 3 presents the effect of core diameter of multi-mode step index silica fiber on the SBS loss in optical fiber cable for three windows of optical fiber communication system. Fig. 3a presents SBS loss in µW and Fig. 4b presents SBS loss in dB. Blue, green and red lines represent SBS loss at 0.89, 1.3 and 1.55 µm wavelengths, respectively. The SBS loss within the optical fiber cable increases with the increase of diameter for the three different windows of optical fiber communication. However, from the numerical comparison results, it is ascertained that SBS loss of the optical fiber is the lowest for 0.89 µm.

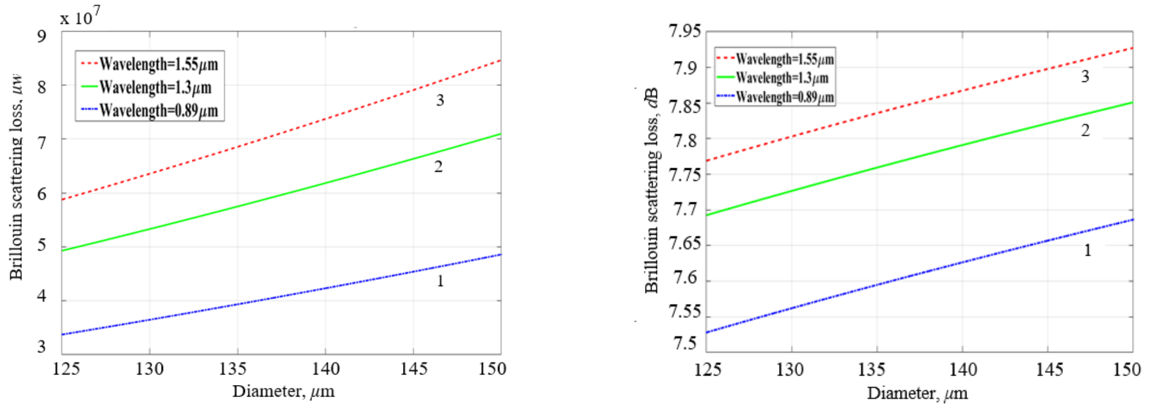
Fig. 4 presents the effect of core diameter of multi-mode graded index silica fiber on SBS loss in optical fiber cable for three windows of optical fiber communication system. Fig. 4a presents SBS loss in µW and Fig. 4b presents SBS loss in dB. Blue, green and red lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively. SBS loss within the optical fiber cable increases with the diameter for these three different windows of optical fiber communication. However, from the numerical comparison results, it is ascertained that SBS loss of the optical fiber is the lowest at 0.89 µm.

Fig. 5 presents the effect of core diameter of step index plastic fiber on SBS loss in optical fiber cable for three windows of optical fiber communication system. Fig. 5a presents SBS loss in µW and Fig. 5b presents SBS loss in dB. Blue, green and red lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively. SBS loss within the optical fiber cable increases with the diameter for the multi-mode step-index fiber. However, from the numerical comparison results, it is ascertained that SBS loss of optical fiber is the lowest for 0.89 µm.



(a) (b)

Fig. 5. Diameter dependence of plastic step index optical fiber for three windows of optical fiber communication system. Blue (1), green (2) and red (3) lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively.



(a) (b)

Fig. 6. Diameter dependence of plastic graded index optical fiber for three windows of optical fiber communication system. Blue (1), green (2) and (3) red lines represent SBS loss for the wavelengths 0.89, 1.3 and 1.55 µm, respectively.

Fig. 6 presents the effect of diameter of multi-mode graded index plastic fiber on SBS loss in optical fiber cable for three windows of optical fiber communication system. Fig. 6a presents SBS loss in µW and Fig. 6b presents SBS loss in dB. Blue, green and red lines represent SBS for the wavelengths 0.89, 1.3 and 1.55 µm, respectively. SBS loss within the optical fiber cable increases with the diameter of cables for three different windows of optical fiber communication system. However, from the graph results, it is ascertained that SBS loss of the optical fiber is the lowest for 0.89 µm.

4. Analysis and discussions

This section presents the performance evaluation of multi-mode step index silica fiber over multi-mode graded index silica fiber. As their core diameters lie in different ranges, the range of losses has been determined with respect to their range of core diameter. Similarly, the performance evaluation of step index plastic fiber over graded index plastic fiber has also been performed in terms of range of losses in dB. The range of SBS loss for the considered four types of cables for three windows of optical fiber communication system is tabulated in Table 2.

Table 2. Range of SBS loss for four types of optical fiber cables for three windows of optical fiber communication system.

Type of fibers	Optical source and detector operation wavelength (µm)	Range of losses (dB)
Multi-mode step index silica fiber	0.89	5.62 – 6.59
	1.3	5.82 – 6.75
	1.55	6.81 – 1.55
Multi-mode graded index silica fiber	0.89	**3.96** – **4.07**
	1.3	**4.13** – **4.29**
	1.55	**4.2** – **4.35**
Step index plastic fiber	0.89	**4.8** – **6.18**
	1.3	**4.95** – **6.35**
	1.55	**5.05** – **6.4**
Graded index plastic fiber	0.89	7.53 – 7.68
	1.3	7.69 – 7.85
	1.55	7.775 – 7.955

From the comparison of ranges of losses, it is clear that between two types of silica fibers, multi-mode graded index silica fiber offers lower loss than that of multi-mode step index silica fiber. However, between the two types of plastic fibers, step index plastic fiber offers lower SBS loss than that of graded index plastic fiber. At a glance from the data presented in Table 2, it is ascertained that plastic step index fiber offers the lowest range of SBS losses among all the others.

5. Conclusion and future recommendation

A comparative analysis of the effect of optical fiber cable diameter on SBS loss in optical fiber communication system has been presented in this paper. The diameter dependence of SBS loss for three windows of the optical fiber communication system has been analyzed considering multi-mode step index, multi-mode graded index silica fiber and plastic fibers as the transmission media. From the outcome of the comparative analysis through a numerical approach, it has been ascertained that the lowest SBS is achieved by using multi-mode graded index silica fiber from the silica fiber category. However, between the two types of plastic fibers, the step index plastic fiber offers better performance. In conclusion, this paper reports that SBS loss is affected by the core diameter and the type of cable. The numerical findings of this research work can be a doorway for the researchers to facilitate better designs of optical fiber cable that offers the lowest SBS loss.

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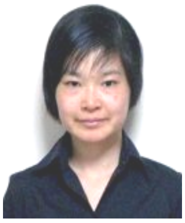

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Вплив діаметра серцевини оптичного волокна на втрати розсіювання Бриллюена

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Анотація. У цій статті повідомлено про вплив діаметра серцевини волоконно-оптичних кабелів на втрати розсіювання Бриллюена, що є однією з основних характеристик втрат у системі зв'язку з оптичним волокном. Аналіз цієї характеристики втрат на трьох вікнах робочої довжини хвилі лазера проведено на основі чисельного підходу. Серед різних типів волоконно-оптичних кабелів для чисельного аналізу були розглянуті багатомодові волокна на основі двоокису кремнію зі ступінчастою зміною показника заломлення, багатомодові волокна на основі SiO_2 з поступовою зміною показника заломлення та пластикові волокна. У цій дослідницькій роботі проведено чисельний аналіз за допомогою MATLAB. Шляхом порівняльного аналізу було встановлено, що на втрати розсіювання Бриллюена впливає не тільки довжина робочої хвилі, але і діаметр серцевини різного типу кабелю. У результаті порівняльного аналізу було виявлено, що втрати розсіювання Бриллюена зменшуються із застосуванням багатомодового волокна на основі SiO_2 з поступовою зміною показника заломлення. Однак у категорії пластикових волокон, волокно зі ступінчастим профілем показника заломлення демонструє кращі показники.

Ключові слова: втрати розсіювання Бриллюена, діаметр серцевини, робоча довжина хвилі, оптичне волокно, поступова зміна показника заломлення, ступінчаста зміна показника заломлення.