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An Overview of Stimulated Brillouin Scattering: characterization and applications

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Abstract. The paper investigates theories of stimulated Brillouin scattering (SBS) as one type of third-order nonlinear optics effect, which is widely used and rapidly developing in optical telecommunication systems. System limitations caused by SBS-induced noise were also considered for digital and analog optical communication systems. The present work provides a thorough examination of the properties of various types of SBS materials, as well as lasers, Brillouin frequency shifter and other devices developed to take advantage of SBS's properties. Lastly, we summarized recent advances made in this field for solving those difficulties and challenges.

Keywords: Optical telecommunication; nonlinear effects; stimulated Brillouin scattering (SBS); Brillouin fiber lasers; Brillouin frequency shifter technique**s.**

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1. Introduction

A major issue in optical telecommunication systems is the nonlinear effects in optical fiber related to vibrational excitation modes of silica. These are the stimulated Raman scattering (SRS) and the stimulated Brillouin scattering (SBS) and they were among the first nonlinear effects studied in optical fibers [1]. The optical fiber serves as a nonlinear, gain-amplifying medium in which the optical field transfers part of the energy to the linear medium from the said stimulated inelastic scattering.

Light sources are an integral part of optical telecommunication systems. Due to the nature of optical telecommunication systems, the design and deployment of light sources for signal generation in an optical telecommunications system is critical. In the case of dense wavelength division multiplexing (DWDM) systems, in which a large number of wavelength sources spaced at 100 GHz, 50 GHz, and more recently, 12.5 GHz, this is an important development in increasing the required carrying capacity of optical telecommunication systems [2, 3].

Fibers are usually considered to be completely passive or linear media. As the input power increases, one expects only a proportional increase in output power. However, at higher input powers, dramatic nonlinear effects can be triggered. These manifest as strong frequency conversion, optical gain and many other effects, generally associated with strong intensities and highly nonlinear materials. About four decades ago it was realized that optical nonlinearity could place an ultimate practical limitation on the power levels used in fiber transmission systems [4, 5].

A description of the optical nonlinearity requires a precise relationship to be established between how the macroscopic dipole moment per unit volume, or polarization P of the material depends upon the strength E of the applied optical field. In the case of conventional, i.e. linear optics, the induced polarization depends linearly upon the electric field strength in a manner that can often be described by the relationship [6]:

$$P = \varepsilon_o \chi^{(1)} E \qquad (1)$$

where ε_o is the vacuum permittivity and the constant of proportionality $\chi^{(1)}$ is known as the linear susceptibility. In nonlinear optics, the nonlinear optical response can often be described by a generalizing equation (1) by expressing the polarization P as a power series in the field strength E as:

$$\vec{P} = \varepsilon_o (\chi^{(1)}.\vec{E} + \chi^{(2)} : \vec{E}\vec{E} + \chi^{(3)} \vdots \vec{E}\vec{E}\vec{E} + ...). \qquad (2)$$

The quantities $\chi^{(2)}$ and $\chi^{(3)}$ are known as second- and third-order nonlinear susceptibilities, respectively and ., : and $\vdots$ represent the product between the susceptibilitiy tensor and electric field. We shall refer to $\vec{P^{(2)}} = \varepsilon_o \chi^{(2)} \vec{E^{(2)}}$ as the second-order nonlinear polarization and $\vec{P^{(3)}} = \varepsilon_o \chi^{(3)} \vec{E^{(3)}}$ as the third-order nonlinear polarization. The second-order nonlinear process includes second-harmonic generation, optical rectification, sum and difference frequency generation and optical parametric oscillation. The third-order nonlinear optical process can occur in both centrosymmetric and noncentrosymmetric media. These processes include third-harmonic generation, four wave mixing and stimulated scattering phenomena. There are three stimulated scattering processes: Rayleigh, Raman and Brillouin. These processes are characterized by the physical mechanism involved in the light medium interaction.

Second- and third-order nonlinear susceptibilities are responsible for many nonlinear effects in optical fibers. Selected processes of the second-order susceptibility $\chi^{(2)}$ and the third-order susceptibility $\chi^{(3)}$ are summarized in Table 1.

Table 1 Selected second- and third-order susceptibility processes.

Identification	Abbreviation	Susceptibility
Pockels effect	PE	Real ($\chi^{(2)}$)
Optical rectification	OR	Real ($\chi^{(2)}$)
Second harmonic generation	SHG	Real ($\chi^{(2)}$)
Sum frequency generation	SFG	Real ($\chi^{(2)}$)
Difference frequency generation	DFG	Real ($\chi^{(2)}$)
Parametric gain	PG	Real ($\chi^{(2)}$)
Self phase modulation	SPM	Real ($\chi^{(3)}$)
Cross phase modulation	XPM	Real ($\chi^{(3)}$)
Stimulated Brillouin scattering	SBS	Imaginary ($\chi^{(3)}$)
Stimulated Raman scattering	SRS	Imaginary ($\chi^{(3)}$)
Coherent anti-Stokes Raman scattering	CARS	Imaginary ($\chi^{(3)}$)
Optical phase conjugation	OPC	Real ($\chi^{(3)}$)
Four-wave mixing	FWM	Real ($\chi^{(3)}$)

Many physical phenomena lead to light scattering. All the optical processes outlined so far involve the interaction of light waves with a medium. The third-order susceptibility $\chi^{(3)}$ is responsible for a number of scatterings and these are characterized by the physical mechanism involved in the light medium interaction.

The spontaneous Brillouin scattering is an inelastic process resulting from the variation due to difference in pressure caused by a scattering of light. The scattered light frequency is Doppler-shifted, the frequency shift being related to the velocity of acoustic waves in the medium [7], 8]. Spontaneous Brillouin scattering is very weak in optical fibers (30 dB weaker than Rayleigh scattering). Of all these processes, the spontaneous Raman scattering is highly inelastic and produces a spectral shift of about 13 THz in silica optical fibers, because it comes from the interaction of light with the modes of vibration of molecules of the medium [9, 10]. The values of these features are grouped in Table 2.

Table 2 Magnitude order of parameters characterizing the scattering processes [11].

Spectral components	Shift frequency (GHz)	Time relaxation (sec)	Gain (m/W)
Rayleigh	0	10^{-8}	$1x10^{-12}$
Rayleigh Wing	0	10^{-12}	$1x10^{-11}$

Brillouin	10	10^{-9}	$5x10^{-11}$
Raman	13000	10^{-12}	$5x10^{-11}$

2. Stimulated Brillouin Scattering in Optical Fiber

The scattering of light is fundamentally linked to the presence of inhomogeneities in the optical characteristics of the optical fiber itself. Spontaneous Brillouin scattering follows from adiabatic density fluctuations, i.e., periodic perturbations of the refractive index generated by acoustic waves (acoustic phonons) of thermal origin. The amplitude of Brillouin scattering is relatively low in a spontaneous regime, approximately 100 times less than the intensity of the Rayleigh scattering [12]. It relates directly to the number of acoustic phonons in optical fiber, which itself is simply determined by the thermal excitation. However, under stimulated conditions, the population of phonons participating in the interaction lies in the strongly non-equilibrium conditions and therefore grows very rapidly.

The efficiency of the scattering process is thus significantly increased, so that at a certain level of intensity optical fiber acts as a mirror and all the additional power is reflected. The phenomenon that causes the stimulation of Brillouin scattering and leads to the creation of acoustic phonons in the presence of light in optical fiber is electrostriction.

The Brillouin threshold is considered as the critical pump power for which the backward Stokes power is equal to some fraction of the pump power [13]. Of utmost importance in most applications is the achievement of a low threshold value. Using bidirectional pumping methods to reduce the SBS threshold, in order to accelerate the SBS establishment time, has also been considered by a number of researchers [14-16]. Modeling of SBS has been developed by McCurdy [17] in order to predict the strength of the phenomenon in optical fibers.

3. Applications of Stimulated Brillouin Scattering

SBS using optical fibers has been useful in a number of applications since it was first demonstrated in 1972. There are many applications of SBS in areas such as Brillouin fiber amplifiers [9], [18], Brillouin fiber lasers [19-21], long-range distributed fiber-optic sensors for strain and temperature [22], and perhaps most interest in SBS has arisen from the use of Brillouin in the shifting of the carrier frequency of an optical signal [23]. Applications of SBS in communications include: frequency selective amplification in optics signal transmission, frequency conversion with amplification and signal processing systems [24-26].

3.1 Brillouin Fiber Lasers

Fiber lasers have gained tremendous interest for applications in optical telecommunication systems as potential compatible laser sources with high output powers and narrow linewidths. One of the important driving forces behind the development of active laser devices is the realization of a new class of laser sources. Fiber lasers, as active devices, are the most recent major activity in glass lasers. Fiber lasers are achieved using silica glass fibers a gain medium. Glass fiber contains a high refractive index core, surrounded by a lower refractive index cladding layer. Glass is suitable for the laser host because of its optical quality, transparency, low birefringence, high optical damage threshold, thermal shock resistance, weak refractive index nonlinearity, high energy storage and power extraction capacities, size and shape scalability and low cost of raw materials. Theses devices offer promise as significant components for use in the telecommunications and sensing industry [2, 27, 28].

Fiber lasers and optical fiber amplifiers actually have a very close relationship. Through a suitable feedback mechanism, an optical fiber amplifier can be converted into a fiber laser. Usually, a system that has light oscillation in a cavity is considered as a laser system while without the oscillation it is considered as an optical amplifier. Optical amplification is produced by the process of stimulated emission induced by population inversion in a lasing medium [29, 30, 28, 24, 31-32].

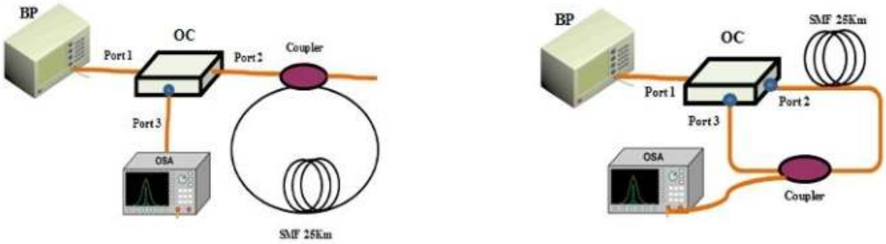
The main operational characteristics of a laser are: the mode content (multimode or single-mode), the operating conditions (pulsed or continuous), the wavelength of operation, and the output power. A low Brillouin threshold makes SBS the dominant nonlinear process in optical fibers and is the main cause of concern in an optical fiber communication system as highlighted in many publications dealing with fiber lasers. SBS has been used in the generation of Brillouin fiber lasers (BFLs) [33].

The threshold for SBS depends upon the bandwidth of the pump source, with a narrow bandwidth producing SBS at low threshold powers in comparison to a broad pump source. Additionally, single frequency operation reduces instabilities in the laser output caused by mode beating of the longitudinal and transverse modes. To summarize, a single-mode laser will dramatically simplify the scattering process and reduce the threshold for stimulated scattering to occur. A continuous operation eliminates any transient effects and also prevents the excitation of Raman phenomena, thus ensuring that only Brillouin scattering is initiated. The pump power required to reach the Brillouin threshold in an optical fiber is inversely proportional to the length of the fiber. Wavelength of operation and careful selection of the pump wavelength can minimize optical loss in the medium through scattering and absorption. The loss mechanisms in optical fibers are Rayleigh scattering and absorption of the radiation by impurities present in the fiber. The amount of scattering and absorption is wavelength dependent. Ideally, the wavelength of the pump laser should operate in a region of low loss. BFLs have a very narrow linewidth and are of interest for a number of applications in optical telecommunication [33].

Brillouin fiber lasers have been produced, using both Fabry-Perot cavity and optical fiber ring resonator [34-37]. The work presented in this dissertation has shown that the SBS process is achieved under most operating conditions. These systems deserve further investigation. The Fabry-Perot Brillouin laser, which has been demonstrated to generate multiple Stokes and anti-Stokes frequencies, is similar to the low reflectivity resonators. In contrast to this, the Brillouin ring laser has the Stokes frequency circulating in one direction and the pump in the other. Therefore, since the two frequencies are not travelling in the same direction, no new frequencies should be produced by four-wave mixing unless the Stokes component becomes intense enough to act as a pump for the second-order Stokes signal to be generated.

The single-mode Brillouin fiber laser has been investigated for several years due to its narrow linewidth (typically from 20 to 50 MHz) for wavelengths in the near infrared, but its magnitude is fairly small [38], [39-42]), very high coherence, low threshold power, directional sensitivity of the SBS gain and high efficiency [34], [43, 44]. In reports of this work, the authors demonstrated a stimulated Brillouin laser with a spectral width of ~2 kHz and an intrinsic linewidth of less than 30 Hz. The generation of multiple Stokes lines can be avoided by utilizing ring cavity BFL [2]. This results in stimulated Brillouin fiber-laser behavior, using a narrow linewidth CW pump and a stabilized fiber ring cavity as reported in [45]. In this paper, a Brillouin fiber laser with 83 m fiber ring cavity, was studied by using a narrow linewidth CW pumped by an argon laser at 5145 Å. The lasing threshold power for the 4.5 μm core fiber was measured at 77 mW and the maximum Brillouin output was 13 mW for a pump of 320 mW. The BFL was demonstrated as a complex configuration to generate Brillouin output power at 13.3 mW for a pump of 320 mW with 70% round trip loss. A stable single-frequency BFL while pumped by a conventional distributed-feedback (DFB) laser diode was demonstrated by J. C. Yong, et al. [43], using an unbalanced Mach–Zehnder interferometer (UMZI). The BFL operates in a single-mode with a linewidth measured to be below 0.94 kHz, the laser-intensity fluctuation was highly suppressed and remains below 4%, Brillouin threshold power and output power were 11.8 mW and 3.18 mW using a pump power of 26.4 mW.

A new configuration for a BFL has been demonstrated using components similar to a conventional BFL [45]. The conventional and the new configuration of the BFL are shown in Figure (1).



(a) (b)

Fig. 1. Experimental set up for (a) conventional BFL and (b) proposed new configuration BFL [45].

In the conventional BFL, the resonator consists of an optical circulator, coupler and SMF acting as a Brillouin gain. The new configuration of the BFL uses components similar to the conventional configuration. The single-mode fiber has length, a mode field diameter and a cut-off wavelength of 25 km, 1161 nm and 9.36 µm respectively, at zero dispersion wavelength of 1315 nm. The optical circulator and optical coupler are the other components required for both set ups with an external cavity tunable laser source (TLS) with a maximum power of ~5.5 dBm. By comparing the output spectrum from the experimental set ups, the proposed BFL configuration experiences a higher output power level than the conventional BFL configuration, as shown in Figure (2). The power difference between these two peaks of lasing signals is 5.7 dB. Following the primary discussion in this dissertation, a more comprehensive study of the use of SBS application in an optical communication system could definitely be provided.

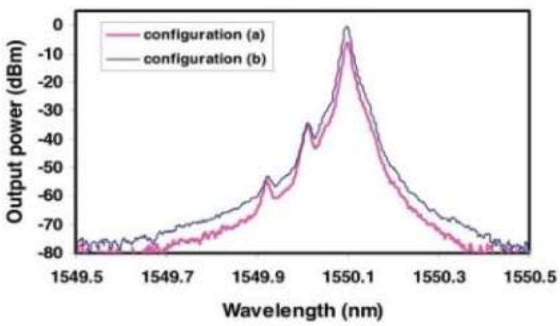


Fig. 2. Comparison of BFL output spectrum between the conventional BFL configuration (a) and the proposed new BFL configuration (b) [45].

By using a pump with narrower linewidth, a shorter length of fiber, and a polarization controller (PC), a high-efficiency BFL was achieved. The effect of polarization in propagating a light wave in the BFL cavity configuration was studied in [46] by employing a three-wave plane polarization controller (PC). A ring cavity of BFL was demonstrated by using a similar configuration as proposed in [46]. High efficiency BFL of approximately 55% was observed as shown in Figure (3), by using a polarization controller (PC). The Brillouin pump was a distributed feedback (DFB) laser diode with narrower linewidth (1 MHz) at 40 mW output power, and a shorter length of fiber (a 3-km G.652 SMF). The ring cavity has a lower SBS threshold 3.6 mW and higher injected pump power 40 mW with output Brillouin power 22 mW and the linewidth was about 5 MHz.

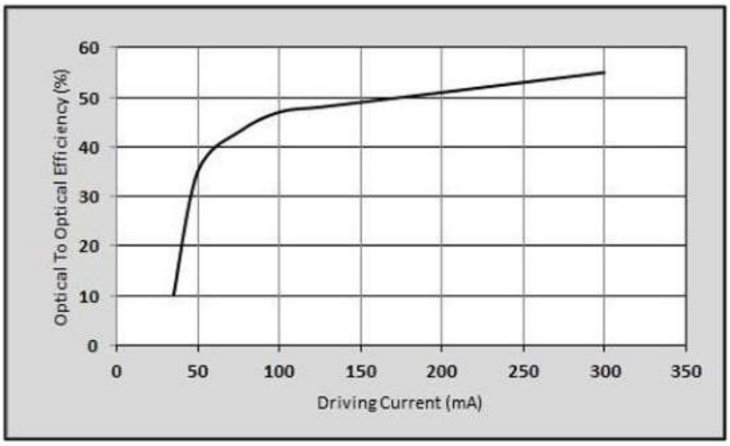


Fig. 3. Relationship between optical-to-optical efficiency and driving current of BFL configuration [46].

Two optical fibers, 170 m single mode fiber with Brillouin shift 10.842 GHz and 100 m true wave fiber (non-zero dispersion-shifted fiber) with Brillouin shift 10.550 GHz, unbalanced Mach–Zhender interferometer (UMZI) made by two fiber couplers and a polarization controller (PC) required for the bi-directional, dual-wavelength Brillouin lasing are schematically shown in Figure (4). The experimental results for the CW lasing show that the higher lasing threshold is 14.1 dBm (25.7 mW). The power of output Stokes wave under increasing pump power is shown in Figure (5).

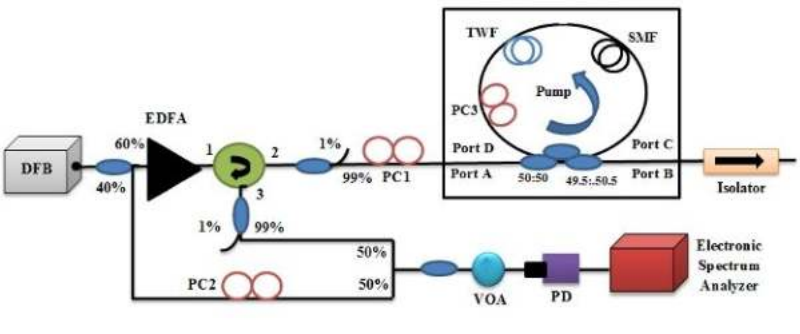


Fig. 4. Schematic layout of the BFL with the hybrid fiber ring cavity for the CW lasing [93].

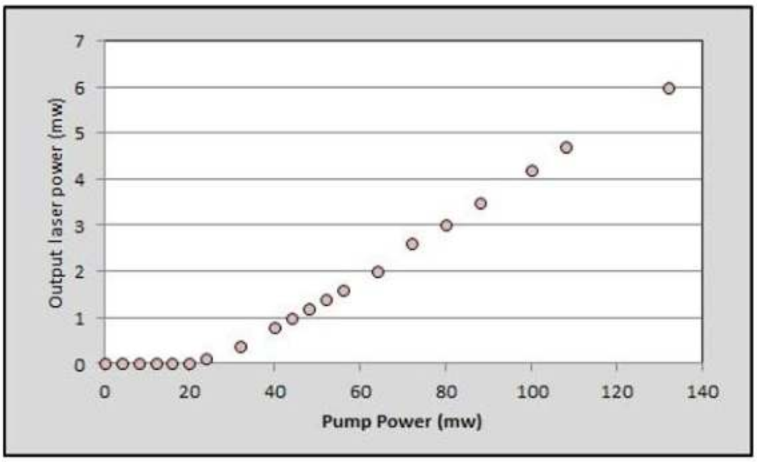


Fig.5. BFL with the hybrid fiber ring cavity output power as function of input pump power [47].

3.2 Brillouin Frequency Shift

The major classification in frequency shift depends upon the acoustic wave generation, either externally to the fiber and then coupled to it (extrinsic devices) or internally within the fiber (intrinsic devices) [48-58]. The optical frequency shift classification is depicted in Figure (6).

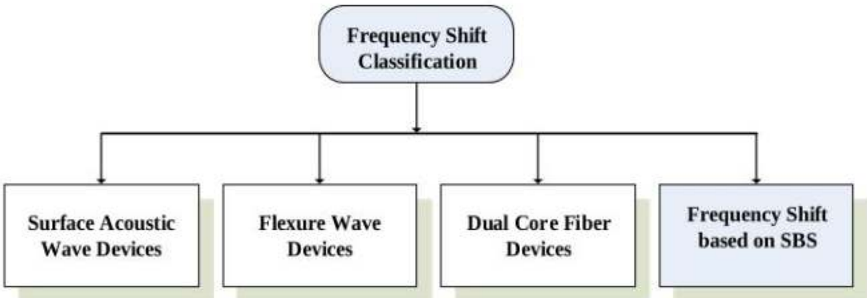


Fig. 6. The frequency shift classification.

Many frequency shift techniques have been investigated. All these devices operate in essentially the same manner, i.e., the interaction of acoustic waves with the guided optical wave. The development of fiber optic-based sensor systems [49] has created a need for an all-fiber tunable frequency shift in order that efficient heterodyne signal processing can be effected. The principle of operation of fiber frequency shift is based on mode coupling within the waveguide, either polarization mode coupling between the eigenmodes in highly briefringent fiber or spatial mode coupling between the LP_{01} and LP_{11} modes in single mode fiber produced by a travelling acoustic wave. Several methods have been reported in which an acoustic wave of wavelength equal to the beat length (was observed directly by means of dipole (Rayleigh) scattering from the fiber) of the fiber is used to couple a guided optical beam from one mode to another, in either a dual moded fiber (LP_{01} to LP_{11}) or in highly briefringent fiber [50, 51] between the non-degenerate LP_{01} modes.

The acoustic wave is generated by acoustic horns, acoustic torsional generators or surface acoustic waves [50-54]. The disadvantages of all these devices, the fact that they must operate at fixed frequencies, will tend to limit their applicability.

3.3 Frequency Shift Based on Stimulated Brillouin Scattering

It is clear that fiber compatible frequency shifts are emerging with a wide frequency spectrum of operation, which overcome many of the disadvantages experienced with Bragg cells. However, all of the devices mentioned in the previous subsection require an electrical input adjacent to the fiber to produce the acoustic energy. Additional optical components to isolate the original carrier and suppress unwanted sidebands are also necessary. Further, the interfacing technique between the acoustic emitter and fiber may be impractical in certain environments. The remainder of this section describes a technique, a purely optical approach to frequency shifting using SBS, which overcomes many of these problems. Longitudinal acoustic modes are generated without recourse to direct electrical transduction. In practice, regarding the devices mentioned in the previous subsection, it is quite difficult to produce a device that operates with reasonable efficiency, good sideband suppression, low power consumption and is mechanically rugged; these devices generally require several watts or hundred of milliwatts of electrical input power. The situation can be improved if the acoustic wave is generated within the fiber. A standing wave generated from difficulty to preventing reflections of the acoustic wave along the fiber as a result both upshifted and downshifted sidebands. The lowest longitudinal acoustic mode, the LP_{01} mode, gives rise to backscattered Stokes-shifted wave whose frequency is downshifted by the characteristic acoustic frequency, the Brillouin frequency shift, by interacting with the input pump wave. About three decades ago it was realized that higher input powers launched into the fiber can cause strong frequency conversion, optical gain, and many other nonlinear effects, generally associated with strong optical intensities and highly nonlinear materials. One of these effects is SBS [5], [8], [59] which is the basis of recently reported frequency shift. The main advantage of this technique is that the acoustic waves are produced within the fiber. The SBS approach to heterodyne carrier generation in fibers makes linear use of the relationship between the Stokes frequency downshift, v_B, and the effective refractive index of the core along which the Stokes signal is generated using [60]:

$$v_{\mathrm{B}} = \frac{n\,K_P V_A}{\pi}\sin\theta \tag{3}$$

where n, K_P, V_A and θ are the refractive index of core, the wave vector of pump wave, the acoustic velocity and the orientation angle between pump and Stokes waves propagation.

The first technique based upon SBS used Argon ion laser sources with pump powers of a few hundred milliwatts (operating at 514.5 nm) and long lengths of optical fiber, typically hundreds of meters. Culeverhouse et al. [60] used two 500 m reels of single mode fiber with slightly different refractive indices. The SBS produced from the two fibers was mixed on a high-speed detector to generate heterodyne carriers of 754 MHz and analyzed with an electronic spectrum analyzer. A single frequency technique that reduces the frequency shift to ~ 10 MHz and greater stability of carrier frequency to environment by mixing the SBS generated along the fast and slow eigenmodes of optical fiber was demonstrated by Duffy et al., [24], [61, 62]. Experimentally by changing a waveguide in a dual-shape core profile, various techniques to control Brillouin frequency shift change have been demonstrated. Most flexible techniques to control the Brillouin frequency shift were investigated by changing geometrical parameters of an optical fiber. The primary interest is in the core structure of an optical fiber because it will affect light wave guiding properties and the Brillouin effect [63, 64]. This work predicted that, as the core radius of optical fiber increases, the Brillouin frequency shift decreases. Theoretically and experimentally. the relationship between the Brillouin frequency shift distribution for a fiber with a non-uniform Brillouin frequency shift along its length and the SBS threshold [65, 66] was investigated. The parameters of the seven different concentrations of F and GeO_2 test fibers used in this work are listed in Table 3.

Table 3 Parameters of test fibers for Brillouin shift measurement at 1550 nm [65].

Fiber	Dopant Concentration of core		Optical loss	Brillouin frequency shift ν_B (GHz)
	GeO_2 Δ (%)	[F] Δ (%)	A (dB/km)	
A	0	0	0.172	11.045
B	0.34	0	0.196	10.837
C	0.83	0	0.208	10.428
D	0.69	-0.30	0.254	10.254
E	0.88	-0.30	0.268	10.097
F	0.98	-0.30	0.313	9.870
G	0.90	-0.70	0.718	9.698

A significant advantage of fiber laser applications is through low Brillouin threshold power. A fiber ring laser can have a relatively low pump threshold power due to low resonator loss. Another technique for frequency shift was demonstrated [67] by using two separate ring resonators, with the pump operating at 632.8 nm, mixed to produce a 20 MHz carrier. For ring finesses of ~ 400, threshold power of 45 μW and a conversion efficiency of 10% were obtained.

4. Conclusions

A review of the fundamental phenomenon leading to the generation of stimulated Brillouin scattering in optical fibers was presented in this work. The paper began with a discussion of the linear and nonlinear effects in optical fibers. Various optical fibers were discussed with an explanation of the advantages of each one as compared to the others. A review of light scattering, the principles of operation and the parameters was also presented. The present work also explains the detrimental effect of nonlinearity in optical fiber due to the low Brillouin threshold and how it can be utilized for producing lasers from a fiber laser source. Out of the many configurations explained, the Brillouin frequency shifter technique was elaborated on further.

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مجلة كلية العراق الجامعة للهندسة والعلوم التطبيقية

نظرة شاملة على استطالة البرلوين المحفزة: التوصيف والتطبيقات

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الملخص . تم في هذا البحث التحقق من نظريات استطارة برلوين المحفزة SBS كاحد انواع تأثيرات البصريات اللاخطية من الدرجة الثالثة ، والذي يستخدم على نطاق واسع وبتطورات سريعة في أنظمة الاتصالات الضوئية .كما تم النظر في قيود النظام الناتجة عن الضوضاء التي يسببها SBS لأنظمة الاتصالات البصرية الرقمية والتناظرية .يوفر العمل الحالي فحصًا شاملاً لخصائص الأنواع المختلفة من مواد SBS ، بالإضافة إلى أشعة الليزر ومبدل تردد البرلوين والأجهزة الأخرى التي تم تطويرها للاستفادة من خصائص استطارة برلوين المحفزة .أخيرًا ، قمنا بتلخيص التطورات الأخيرة في هذا المجال لحل تلك الصعوبات والتحديات.