Chapter 1:

Introduction

1.1 Introductory Remarks

The invention of lasers has turned optics and atomic physics into a dynamic and much-sought after area of research; the restriction of low field intensity is removed, thus allowing some interesting material effects which are depends nonlinearly on the incident field strength. One of the most extremely attractive features of nonlinear fiber optics is the advent of optical fiber lasers which are lasers in which the active gain medium can be constructed by an optical fiber doped with rare-earth elements such as erbium, ytterbium, and thulium. However, using nonlinear effects, such as stimulated Brillouin scattering and stimulated Raman scattering, we can also provide gain in an optical fiber for generating Brillouin fiber lasers (BFLs) and Raman fiber lasers respectively. The former is the aim of this work. The low intensity and low frequency noise and movable focusing as one of the many benefits of fiber lasers resulted in a variety of applications such as microwave photonics [1], spectroscopy [2], coherent optical communications [3], coherent lidar detection [4], interferometric sensing material processing [5], and for medical purposes as well [6]. BFLs have also generated interest for a number of other applications such as gyroscopes due to their extremely narrow linewidth which could be a few Hz [7-10]. In this work, we are going to discuss BFL generation and BFL linewidth measurement; therefore a brief discussion on BFLs as a preamble to the rest of this work will follow in the following section.

1.2 Stimulated Brillouin Scattering in Optical Fibers

What we frequently refer to as reflection of light is actually due to Rayleigh scattering; scattering of light in a medium where the refractive index is random only on a scale smaller than the optical wavelength is called Rayleigh scattering [7]. This scattering is also known as elastic scattering and is a fundamental loss of propagating light for which the frequency of scattered light remains unchanged. On the other hand, the frequency of the scattered light is shifted downward during inelastic light scattering such as Brillouin scattering, or Raman scattering [8]. In the Brillouin light scattering phenomenon, an incident optical wave field is scattered by thermally excited acoustic waves in a medium. The first theoretical study of the Brillouin light scattering by thermal phonons (related to vibrations of the medium molecules by the acoustic waves) was done by Mandelstam in 1918 [9], [10]; however, Mandelstam’s paper was published only in 1926 [11]. Independently, L. Brillouin predicted light scattering from thermally excited acoustic waves in 1922 [12]. Later, Brillouin’s prediction was confirmed experimentally by E. Gross in liquids and crystals in 1930 [13], [14].

Stimulated Brillouin scattering (SBS) occurs when the interference between pump light and the back scattered downshifted light (Stokes wave) reinforces the acoustic waves [15]. SBS can be detrimental in coherent optical-communication systems so that we have to limit the signal power below the SBS threshold which is typically a few miliwatts [16]. However, it has been used advantageously for some practical applications such as optical-fiber characterizations [17], distributed temperature measurements [18], distributed strain measurements [19], distributed attenuation measurements [20], narrow bandwidth amplification [21], frequency shifter [22], and microwave-frequency generation [23]. In addition, the greatest interest of the SBS usage lays in Brillouin fiber lasers (BFL) [24], [25]. As a very highly coherent light source, BFLs have generated interest for a number of applications such as optical sensors and gyroscopes [26] due to their extremely narrow linewidth which could be a few Hz [27], [28], [29].

1.3 Brillouin Fiber Laser – A Review

A fiber laser is usually refers to a laser with an optical fiber as a gain medium. In most cases, the gain medium is a fiber doped with rare-earth ions such as erbium (Er^{3+}), neodymium (Nd^{3+}), ytterbium (Yb^{3+}), thulium (Tm^{3+}), or praseodymium (Pr^{3+}) pumped by laser diodes to generate a linear gain media in these fibers. Although different types of dopants in different host materials such as silica and fluoride give different characteristics of the laser systems, erbium in a silica host is widely used especially in erbium-doped fiber lasers since such lasers are useful in the commercial band of wavelength 1.55 μm for some applications such as optical communication, ultrafast phenomena, and fiber-based sensors. However, BFLs can be generated in any wavelength since they use a nonlinear Brillouin gain in an optical fiber.

BFLs have many specific features making it different from standard lasers with inverted population media. First of all, its coherence should meet radically different requirements so that the BFL is pumped by other lasers called Brillouin pumps (BP) with spectral selection of radiation. Here, the quantity of major importance is the difference $\Delta\omega$ in the BFL and pump frequencies rather than their exact absolute values. As soon as the pump power exceeds the SBS threshold power, the BFL oscillation, generated by adding a proper feedback to the SBS system in the form of a Fabry-Perot (linear) cavity or ring cavity, will set in at a frequency separated from the BP frequency by $\Delta\omega$ due to the Doppler effect for the backward BP inelastic scattering by a moving grating generated via the electrostriction phenomenon. In this thesis, a 25 km single mode fiber is used as the nonlinear gain medium in the two configurations that are the Fabry-Perot (linear) cavity and ring cavity. A relatively long fiber is usually used to generate BFLs which rely on the Brillouin gain associated with the fiber nonlinearity. Indeed, long interaction distances of light propagation are usually needed to achieve the nonlinearity mixing of any significance along the fiber so that the SBS process can be phase matched, or nearly so, to allow the SBS signal to grow to appreciable levels.

Ring cavities are often used to obtain BFLs. In a conventional ring cavity in fiber optics, a fiber is connected between two opposite ports of a 2×2 coupler and an 3 port optical circulator (OC) is spliced to the coupler at port 2 of the OC. The BP is then emitted to the fiber through ports 1 and 2 of OC. The isolators included in the OC operate to ensure unidirectional operation. Due to the nature of SBS, the BFL oscillation is in the opposite direction of the BP oscillation in the fiber. A fraction of the BFL is extracted by the coupler and it is sent to an optical spectrum analyzer (OSA) through ports 2 and 3 of the OC. Nevertheless, a ring cavity can also be made without using the coupler, resulting in an all-fiber cavity with higher output BFL power [30]. The ring cavity has a lower roundtrip loss in comparison to a linear cavity due to it using only one coupler and one optical circulator. A linear (Fabry-Perot) cavity requires basically two mirrors for input and output and a gain (active) medium. In fiber optics, an optical circulator in which the ports 1 and 3 are connected to each other can be used in place of the aforementioned mirrors so that an optical fiber as a gain medium is spliced between both ports 2 of the two optical circulators. In a conventional linear configuration, a 2×2 coupler is used between ports 2 of the two OCs to inject the initial laser and to extract the output spectrum. However, as it will be shown in this thesis, our proposed configuration can be more optimistic with higher efficiency [31]. In the other linear BFL configuration, a fiber Bragg grating is used instead of the OC to force the laser to operate in a single longitude mode [32], [33].

1.4 Objective of This Thesis

The generation of high power lasers has always been a topic of laser researches. Some researches have been done to improve the Brillouin fiber laser (BFL) power [33]. However, the generated BFL peak power is lower than the transmitted Brillouin pump peak power in the previous works. In addition, there are various reported values from a few Hz to a few KHz about BFL linewidth [34], [35], [36]. Therefore, the aim of this research is to improve BFL power and to measure the ultra-narrow BFL linewidth. In this research, as we shall soon show, displays high power BFL especially in linear cavities in addition to a different linewidth for BFLs [31], [37].

1.5 The Research Methodology

After a literature review about BFLs, the generation of BFLs in both linear and ring cavities will be studied. Then, by changing cavity parameters such as coupler ratios, component locations, and by using available components, new BFL cavity configuration will be demonstrated to generate high power BFLs. Finally, as a challenging issue, the linewidth of BFLs will be measured and it will be compared with the measured BP linewidth.

1.6 Thesis Overview

This thesis consists of 5 main chapters. After the introduction in chapter 1, the propagation of electromagnetic waves in optical fibers is reviewed in chapter 2. Then, we discuss the theoretical backgrounds of nonlinear optics leading to the explanation of stimulated Brillouin scattering (SBS) as a kind of nonlinear phenomena. The theory of BFL generation in ring and linear cavities as an application of SBS is presented in this chapter by discussing the three-wave model of SBS. A review of some important parameters is also discussed at the end of the chapter 2.

In the chapter 3, after observing Brillouin scattering and SBS in a free end single-mode fiber, we investigate the effect of fiber length and Brillouin pump linewidth on SBS. SBS threshold power as the important factor in SBS will be discussed. All experimental methods in determining SBS threshold power will be explained. Then the generation of high power BFLs is considered in the both ring and linear cavities. The BFL power generated in the proposed linear and ring cavities will be compared by the BFL power resulted in the conventional ones.

In the chapter 4, after discussing the homodyne and heterodyne linewidth measurements, we measure a tunable laser source (TLS) linewidth by using the heterodyne method between the TLS and an independent BFL. The BFL is generated in a conventional ring cavity by using the narrow linewidth TLS setting. Then, the BFL linewidth is also measured by the same method between the two independent BFLs for the both narrow and wide TLS linewidth settings.

Chapter 5 is devoted to the conclusion which summarizes all researches done in this work about the high power BFLs and the BFL linewidth measurements.

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