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Tuneable high output power Brillouin fiber laser

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A highly efficient tuneable Brillouin fiber laser (BFL) amplified by Er^{3+}/Yb^{3+} co-doped double-clad fiber amplifier (EYDFA) is demonstrated. In this work, a ring BFL and a double-pass EYDFA are used as a seed oscillator and power amplifier, respectively. With 10 km long non-zero dispersion shifted fiber (NZ-DSF), the seed BFL has the maximum output power of -5 dBm, side mode suppression ratio of 30dB and stimulated Brillouin scattering (SBS) threshold of 5 dBm. The amplified BFL output has the maximum output power of 400 mW and a side mode suppression ratio of more than 50 dB. The EYDFA provides a flat gain in the wavelength region of 1545 nm to 1566 nm.

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1. Introduction

In recent years, single transverse mode fiber lasers have been demonstrated with output powers in the kilowatt regime and linewidths of about 10 - 20 nm [1]. This broad linewidth poses no problems for many applications, such as welding and cutting. However coherent laser sources with both low intensity noise and low frequency noise are an essential requirement in the other applications such as coherent optical communications, coherent LIDAR detection, wavelength conversion, high-resolution spectroscopy, interferometric sensing and fiber gyros. On the other hand, some applications such as gravitational wave detection and digital or analogue optical transmission require high power narrow linewidth lasers and in some other applications there is a need for stable electric signals ranging from hundreds of gigahertz to terahertz with dual frequency narrow linewidth lasers [2-3].

Single-frequency solid-state lasers including fiber laser are the best-known low-noise coherent seed laser with a spectral linewidth ranging from hundreds of kilohertz to as narrow as a few kilohertz [4]. Being relatively safe and immune to electromagnetic disturbance, the narrow linewidth fiber lasers (NLFLs) can produce near-quantum-limited intensity noise by using an electronic feedback loop and amplitude squeezed pump diode. There are several efficient methods to generating narrow-linewidth fiber lasers, including using one section of gain fiber as the saturable absorber which acts as a very narrow filter, twisted-mode technique to restrain spatial hole burning effect in the laser material, and fiber Bragg grating (FBG) [5-7]. Single-frequency Brillouin fiber lasers are another type of highly coherent light source whose linewidth could potentially be only a few Hz [8-9]. BFLs exploit stimulated Brillouin scattering (SBS) which is a nonlinear effect originated from the interaction between an intense light (Brillouin pump (BP)) and thermally excited acoustic waves in a medium. The thermally excited acoustic waves generate an index grating that co-propagates with the pump at the acoustic velocity in the medium. This moving grating reflects the pump light and causes the backscattered light or Brillouin Stokes to experience a downshift in the frequency as a result of Doppler effect. The Stokes linewidth becomes several orders of magnitude narrower than that of the BP beam [10].

Some applications such as digital or analog optical transmission need high power tunable single-frequency fiber lasers [11]. The high power fiber lasers can be realized by exploring efficient, high power pump light sources, and co-dopant novel fiber designs for effective absorption of pump power [12]. Indeed, optimization of fiber material and improvement of the effectiveness of absorption can be achieved by co-doping Ytterbium ions into the erbium-doped fiber as a sensitizer and double cladding the fiber structure to expand the aperture of the pump light [13]. Co-doping with Ytterbium prevents the formation of Erbium clusters by effectively controlling the upconversion from $^4I_{13/2}$ level and therefore a higher doping level can be used in the fiber so called Erbium-Ytterbium doped fiber (EYDF) [14]. The high power laser can be used to significantly influence on the operation of optical transmission systems which use narrow-linewidth single frequency lasers [15]. Unlike conventional fiber lasers, high-power single-frequency fiber lasers can be coherently beam-combined. High spectral quality can be achieved by switching from an oscillator to a master-oscillator power amplifier (MOPA) configuration. MOPA configurations can provide highly controllable single-frequency radiation for which the output can be tunable, frequency-swept and pulsed. Because of the cavity-free travelling-wave nature of the amplifiers, they can maintain the spectral purity of the seed source with a minimum addition of phase noise. Furthermore, this configuration allows beam combination for power scaling.

In this paper, a double-pass Erbium Ytterbium doped fiber amplifier (EYDFA) is used for amplification of a tunable narrow linewidth BFL. The performance of the seed BFL is investigated for two different nonlinear gain media which are non-zero dispersion shifted fiber (NZ-DSF) and conventional single mode fiber (SMF). The gain characteristic of the EYDFA is also examined. The output characteristics of the amplified BFL in term of linewidth and output power are also presented.

2. Experimental setup

The configuration of the proposed high power narrow linewidth BFL, which is amplified by the EYDFA is shown in Fig. 1. It consists of three main parts, namely a tunable narrow linewidth BFL oscillator operating in C-band, a single mode Erbium-doped fiber amplifier (EDFA) or pre-amplifier and a cladding pumped EYDFA. The EYDFA uses a 10 m long EYDF as a nonlinear gain medium. This length is chosen to reduce undesirable nonlinear scattering effects inside the MOPA system. The EYDF has an absorption coefficient of approximately 0.5dB/m at 915 nm for Ytterbium ion with the core and outer cladding diameters of 6 µm and 130 µm respectively. The erbium peak absorption is 40dB/m at wavelength of 1535 nm. The pump light from a 927 nm multimode laser diode (MMLD) is coupled into the double-clad EYDF by a multimode combiner (MMC) with a numerical aperture (NA) of around 0.15. Since the amplified spontaneous emission (ASE) from the EDFA becomes a source of optical noise, a tunable band pass filter (TBF) is used to filter the forward ASE from entering the EYDFA. The TBF has a transmission bandwidth of 1.0nm and insertion loss of around 0.5 dB.

It is easier for the ring fiber laser to achieve narrow linewidth fiber laser compared to that of linear cavity based fiber laser. In addition, the conventional linear cavity BFL usually suffers from problems such as the higher-order Stokes generation [8]. Therefore, we use a ring cavity for the seed BFL oscillator as shown in Fig. 1. The seed BFL consists of an optical circulator, a 50:50 optical coupler and a piece of 25 km long SMF or 10 km long NZ-DSF. A tunable laser source (TLS) with the maximum pump power of around 9 dBm is used as a BP. This TLS can be tuned from 1520 nm to 1620 nm with a stable output linewidth of approximately 15 MHz [9]. The BP was directed into the Brillouin fiber to create the narrow linewidth Stokes in the opposite direction. The coupler allows a certain ratio of the light to oscillate in the cavity and the remainder to couple out through the circulator. The output BFL wavelength is around 1550 nm with 100 nm tuning range due to TLS tuning wavelength region. Since the effect of polarisation on the performance of the BFL is negligible, the polariation controller device is not used in the ring BFL. The experiments are separately carried out for a 10 km long NZ-DSF and a 25 km long SMF as the gain medium for the BFL. The 25 km long SMF has a mode field diameter (MFD) of 9.36 µm, a cut-off wavelength of 1161 nm, a zero dispersion wavelength of 1315 nm, and an attenuation coefficient of 0.187 dB/km at 1550 nm. The NZ-DSF has an MFD of 8.5µm, a cut-off wavelength of 1171 nm and a positive dispersion at 1550 nm (OFS, TW-SMF, D = 4.0 ps/nm/km). The loss of the NZ-DSF is less than 0.02 dB/km. The NZ-DSF has a smaller core diameter compared to the SMF and therefore the effective length, Brillouin threshold and linewidth are different for both BFLs. In this work, the performance of the amplified BFL is compared for two different seed BFL.

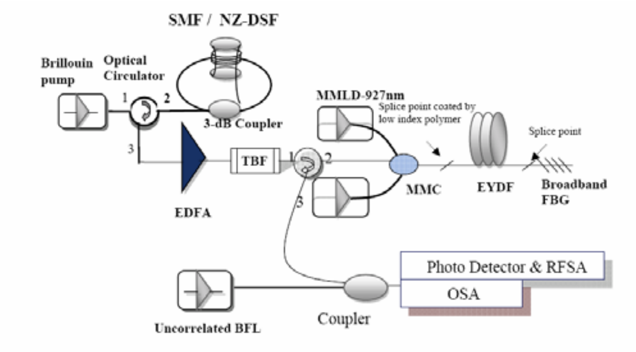

Fig. 1. Experimental set-up for the linewidth measurement of the BFL amplified by the proposed double-pass EYDFA configuration.

In order to improve the quantum efficiency of the double clad EYDFA, the BFL is pre-amplified by the EDFA up to saturation input power of 5 dBm. The EDFA employed a 3 m long highly doped Erbium-doped fiber (EDF) with an absorption rate of 13 dB/m at 975nm, numerical aperture of 0.23 and background loss of 40dB/km, which is forward pumped with a 980nm pump. Then, the pre-amplified BFL is injected into the EYDFA from port 1 through port 2 of the optical circulator and this circulator also functions to route the amplified BFL into port 3 as an output. A broadband fiber Bragg grating (FBG) with reflectivity of more than 99% and a bandwidth of 40nm centred at 1545nm is used to allow the input BFL signal to double-propagate in the gain medium. The output power and attenuated spectrum of the amplified BFL are measured by a power meter and an optical spectrum analyser (OSA), respectively. In the experiment, the input signal power of EYDFA and the multimode 927 nm pump power are fixed at 5 dBm and 4 W, respectively.

Although laser linewidth can be measured by the homodyne method in which a signal is mixed with its time-delayed replica, achieving incoherent self-mixing of BFL is difficult in practice since the coherence length is estimated to be at least hundreds of kilometres [4]. Besides, this method is sensitive to environment perturbations although insensitive to fluctuations in the frequency of the laser itself [16]. In our work, the laser linewidth measurement is done by evaluating the beat signal resulting from the interference of the BFL with another uncorrelated BFL using a heterodyne beat technique [9],[17], [18]. This method requires another laser either with a comparable well-known spectrum or with an extremely narrow and negligible linewidth. The linewidth of the amplified BFL is measured by combining the attenuated BFL signal with another uncorrelated BFL using a 3 dB coupler in this work. The uncorrelated BFL frequency should be very close to the output BFL frequency. The wavelength separation between both signals should be less than 0.01nm so that the frequency of the beat wave generated in the output coupler is within a radio-frequency spectrum analyzer (RFSA) wavelength region [19]. The combined output is converted into electrical signal by a fast-response photo detector and the generated radio beat frequency signal is analyzed by an RFSA. It is expected that the BFL is able to demonstrate a linewidth in the region of less than a few hundred MHz to a few Hz. The advantage of the proposed technique is its simplicity which requires only widely available standard optical components [9]. The photodiode has a bandwidth of about 6 GHz while the RFSA (ANRITSU MS2683A) has a resolution bandwidth of 300 Hz to 3 MHz and frequency range of 9 kHz to 7.8 GHz. The accuracy of the linewidth measurement is limited by the resolution of the RFSA.

3. Result and discussion

Fig. 2 shows the output spectra of the seed BFL oscillator with different Brillouin gain media; SMF and NZ-DSF. The BP pump power is fixed at 9 dBm in both BFLs. As shown in Fig. 2, the line spacing between BP reflection and BFL peak powers is measured to be approximately 0.083 nm, and the peak power for both lasers are obtained at around -5 dBm. The side mode suppression ratios (SMSR) of 29 dB and 30dB are achieved with the usage of SMF and NZ-DSF, respectively. Both BFL lines have 3dB bandwidth of less than 0.015nm limited by the OSA resolution of 0.015 nm. Inset of Fig. 2 shows the peak power of the amplified BFL against the BP power. As shown in the inset, the SBS power for both lasers rises as the BP power increases. Both peak powers saturate at BP pump power of around 10 dBm due to the generation of the second-order Stokes, which is co-propagating with the BP. At lower BP power, only a single-wavelength of the first Stokes line is obtained for both BFLs with SMF and NZ-DSF as shown in Fig. 2. The SBS threshold power is defined as the BP power at which the peak power of BP reflection equals the Stokes peak power [20]. Therefore, the SBS threshold is measured to be around 5 dBm and 4 dBm for NZ-DSF and SMF, respectively. From this experimentally determined threshold values, one can estimate the Brillouin gain coefficient which is about 1.253×10^{-11} m/W for the NZ-DSF [10]. It is also observed that the threshold is relatively unchanged with the operating wavelength. The threshold change with output power can be neglected.

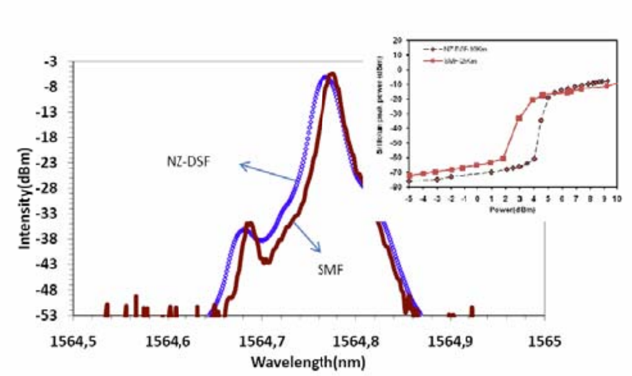

Fig. 2: Output spectra from the BFL oscillator with SMF and NZ-DSF. Inset shows the peak power against BP powers.

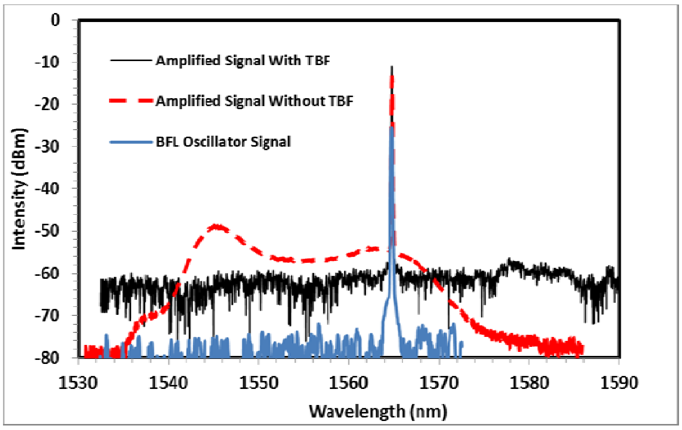

Fig. 3. The output spectra of the BFL amplified by the double-pass EYDFA

The double pass EYDFA is used in the proposed MOPA system to provide a higher gain due to the double-propagation of the signal in the gain medium in comparison with a single-pass EYDFA. Fig. 3 compares the attenuated output spectrum of the proposed BFL, which is amplified by the double-pass EYDFA in the MOPA system with and without a TBF. Without the TBF, the forward ASE of the pre-amplifier enters the double-pass EYDFA, which reduces the attainable gain of the amplifier while maintaining the noise level. The lower gain in turn reduces the signal to noise ratio (SNR) of the amplified BFL. Therefore, with the incorporation of the TBF, the SNR is improved from 41 dB to 50 dB as shown in Fig. 3. These SNR values indicate that the measured output power is mainly from the peak region of the amplified signal.

Fig. 4 shows the output power of the amplified BFL (with NZ-DSF) against the input pump power of the double-pass EYDFA at the various input BP wavelengths and powers. Inset of Fig. 4 shows the gain of the amplified signal at different BP wavelengths at various input signal power of the BFL when the 927nm pump power is fixed at 4.1 W. As shown in Fig. 4, the maximum output power of 400 mW that corresponds to the gain of 33.6 dB is achieved when the BP wavelength and 927 nm pump power are fixed at 1557.4 nm and 4.1 W, respectively. As shown in the inset of Fig. 4, the flat gain of 33.5 dB is observed with a gain variation of less than 1dB within a wavelength region of 1545 nm to 1566 nm especially at the input signal BP power of -10 dBm. Fig. 4 also shows that the output power increases from 320 mW to 400 mW as the input BP power increases from -10 dBm to 5 dBm at the BP wavelength of 1557.37 nm. This translates into the conversion efficiency power of about 10%.

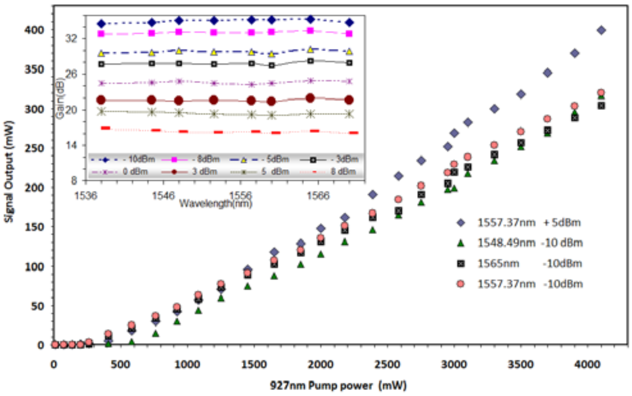

Fig. 4. The output power of the amplified narrow BFL signal versus MMLD pump power at the wavelength 927 nm for the various BP signal wavelengths and the BP signal powers. Inset shows the gain of amplified signal for the different BP wavelengths at using the fixed MMLD pump power 4.1 Watt.

Fig 5 shows the beat spectrum of the amplified BFL and the uncorrelated BFL from the 25 km SMF. Here, we use the TLS with a linewidth of 15 MHz as a BP to generate a narrower linewidth BFL. The BFL linewidth is reported to be proportional to the BP linewidth [21]. It is also reported that the BFL Stokes linewidth slightly shrinks and its Lorentzian line shape changes to Gaussian shape as the BP power increases [22]. As shown in Fig. 5, the output beat spectrum of the Brillouin has a single peak frequency at around 1.995 GHz which indicates a single frequency operation of the BFL. The full width at half maximum (FWHM) of the BFL line is measured to be around 10 kHz, which is wider in comparison with the last measured linewidth [9]. This result is expected as the broadening of the amplified BFL spectrum is evident in Fig. 2. The actual linewidth is expected to be smaller than 10kHz since the beat linewidth is the convolution of both TLS and the amplified BFL linewidth. More accurate linewidth measurement can be obtained by using a self-heterodyne technique. This measurement cannot be carried out in our laboratory at this moment due to unavailability of a suitable electrical spectrum analyser.

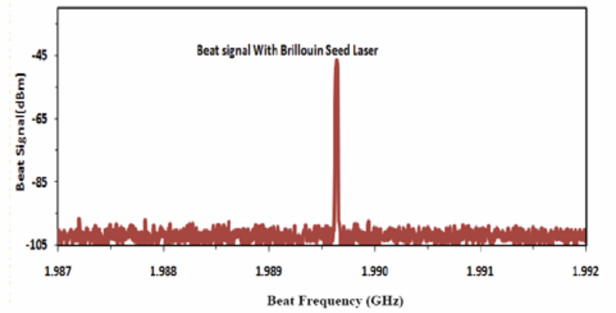

Fig. 5. The measured heterodyne beat frequency spectra by using a piece of SMF as the Brillouin nonlinear gain medium.

4. Conclusion

The performance of a narrow linewidth BFL, which is amplified by a cladding pumped EYDFA in a MOPA system is experimentally demonstrated. The amplified BFL linewidth is measured to be about 10 kHz in the wavelength region from 1545 to 1566nm. Since the BFL linewidth was reported to be a few Hertz, it is concluded that the amplified BFL linewidth is broadened as it propagates inside the EYDFA. The amplified BFL has achieved the maximum output power of 400 mW with the maximum 927nm pump power of 4.1W at the BP power and wavelength of 5 dBm at 1557.37 nm, respectively. The power conversion efficiency is calculated to be approximately 10%.

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