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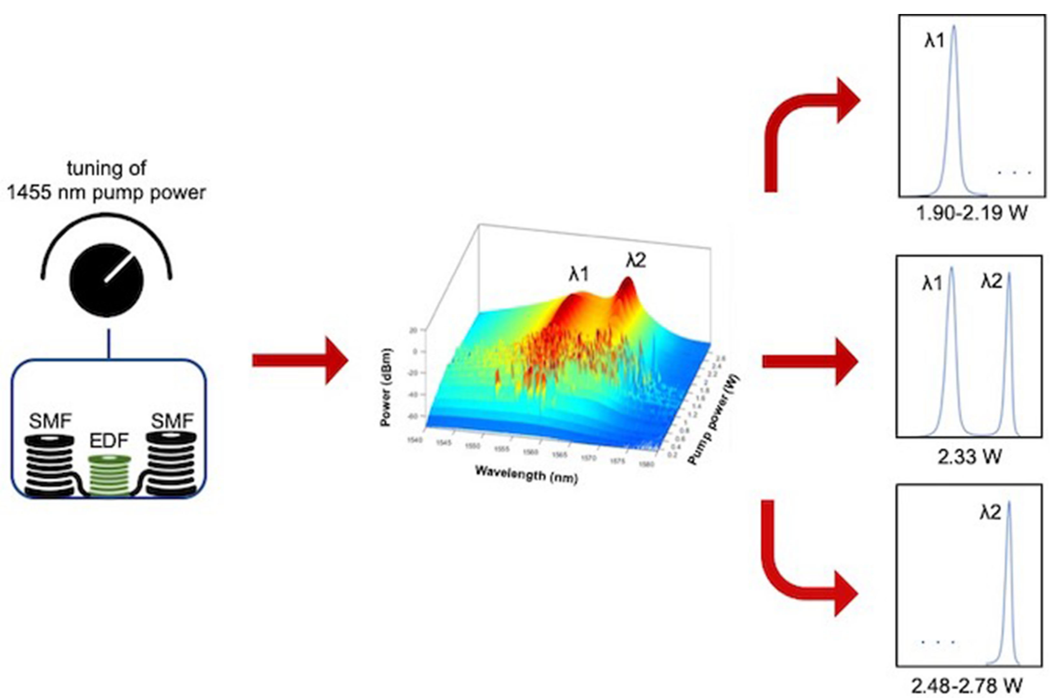

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Open Cavity Controllable Dual-Wavelength Hybrid Raman-Erbium Random Fiber Laser

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Abstract: This investigation demonstrates a simple open-ended controllable dual-wavelength random fiber laser based on hybrid amplification of the Raman and erbium-doped fiber (EDF). Bidirectional pumping is employed to power a 80 km Truewave REACH fiber and a section of EDF as the gain medium. Without cavity selectors and reflectors, a single or dual wavelength operation is obtained by pump power variation. Interchangeable lasing peaks are obtained at wavelengths 1557 and 1567 nm, and both with peak power discrepancies of 16.2, 18.3, and 0.1 dB, respectively. The proposed scheme presents opportunities for long distance applications utilizing single laser, dual laser, or combination of both.

Index Terms: Fiber lasers, random fiber lasers, stimulated Raman scattering, erbium.

1. Introduction

Controllable multiwavelength fiber lasers have always been a subject of interest due to its potential and versatility in applications such as fiber optic sensing, wavelength division multiplexing fiber communication system, and optical component characterization. Stemming from the same category is the controllable dual-wavelength fiber laser which is a prerequisite in some applications such as self-mixing interferometry-based sensors, signal generation, and differential absorption measurement. The switching or controlling effect in fiber laser is typically achieved by using a selective wavelength mechanism by embedding it within the multiwavelength laser itself or combining it with the laser via a supplementary cavity. Some of the controlling effect in fiber lasers utilizing wavelength selectors/reflectors can be realized through spectral polarization-dependent control [1]–[4], core-offset adjustment [5]–[7], microbend deformer to change the mode coupling condition [8], variable optical attenuators [9], [10], modifying the reflection of Sagnac loop mirrors [11]–[15], and through designing the cascaded cavity losses that correspond to different lasing wavelengths [16]. The similarity of the aforementioned setups is the use of erbium-doped fiber (EDF) as the gain medium. EDF is a great gain medium for multiwavelength laser generation for several reasons. It requires very little power to excite and its broad bandwidth overlaps the entire C-band with high gain. However, the main issue with the employment of EDF is the cross-saturation effect originating from the homogenous gain broadening, which causes instability at room temperature. Apart from designing different overlapping cavities to share the same gain medium, several techniques can be employed to stabilize the generation. Some include introducing inhomogeneity within the gain medium by using elliptical core EDF, twin-core EDF, utilizing polarization hole burning effect, integrating other gain mediums with high nonlinearity to instigate four wave mixing (FWM), or using semiconductor optical amplifiers or Raman gain mediums that are much stable at room temperature [17]–[23].

In recent times a new kind of fiber laser has been introduced which exploits random scattering in an amplified gain medium to incite lasing, named as the random fiber laser [24], [25]. Propagating light is scattered multiple times via Rayleigh scattering, increasing the mean path length of photons to acquire gain. Not only that, the scattering events assemble optical feedback in what is known as the random distributed feedback to accomplish cavity resonance. These appealing features also enable random fiber lasers to be constructed without traditional resonators. This has prompted many research groups in attempt to simplify existing fiber laser systems via random lasing and even venture into new application ideas unique to the randomness of the laser [26]–[30].

Despite the many fiber laser applications realized using random lasing, there is an apparent gap within the field in the development of fiber laser systems that employ pure random feedback (cavity without reflectors). This is because most investigations are highly focused on combining the conventional lasers with random mirrors and vice versa as it guarantees easily-acquired stable lasing. Therefore, the only investigation on controllable multiwavelength random fiber laser is [31]; a ring cavity composed of a programmable tunable filter and EDFA, which is assisted by random mirror excited via Raman gain to stabilize the laser generation.

In this paper, an open-ended controllable Raman-erbium dual-wavelength random fiber laser based purely on random distributed feedback is experimentally demonstrated. A preliminary study of EDF length impact on the hybrid laser scheme is presented, to derive the proposed scheme. The scheme is driven by a single pump source to power both the Raman and erbium gain in the absence of selective wavelength components and reflectors. The controlling capacity revolves around two wavelength peaks (1557 nm and 1567 nm), which allows for a single or dual wavelength operation simply by tuning the pump power. To the best of our knowledge, the proposed scheme is the simplest controllable dual-wavelength random fiber laser configuration that is able to operate without wavelength filters.

2. Impact of EDF Length on Hybrid Raman-Erbium Random Fiber Laser

Fig. 1 portrays the schematic diagram of the (Hybrid Raman-Erbium Random Fiber Laser) HRFL. A 1455 nm Raman pump unit (RPU) with maximum pump power of 2.78 W is employed with backward reflection precaution using an isolator (ISO-1). Pump power is distributed equally through both wavelength division multiplexers (WDM-1 and WDM-2) via a 3-dB optical coupler (OC-1), which forces the pump signal to propagate in opposite directions in the gain medium. This also ensures a uniform inversion in the HRFL gain medium [32], comprising of a section of EDF spliced between 90 km long Truewave REACH fiber (TW fiber). It is a single mode fiber that is claimed to have the highest Raman gain efficiency on the market. Meanwhile, the EDF used is OFS RightWave LSL EDF with peak absorption of 3 dB/m at the 1455 nm pumping wavelength and peak absorption of 16 dB/m at 1530 nm wavelength [33]; and is varied in length as part of the investigation from 10 m to 50 m with intervals of 10 m length. Both cavity ends are terminated by an isolator (ISO-2 and ISO-3) to avoid Fresnel reflection and to ensure optical feedback is exclusively from Rayleigh scattering. 99/1 power couplers (not shown in schematic) are inserted just after the isolators for the purpose of spectral and output power measurements. Due to the symmetrical design of the scheme, it is sufficient to acquire spectral measurements from any one output port as the results will be identical. However, the power measurements will be a summation from both output ports.

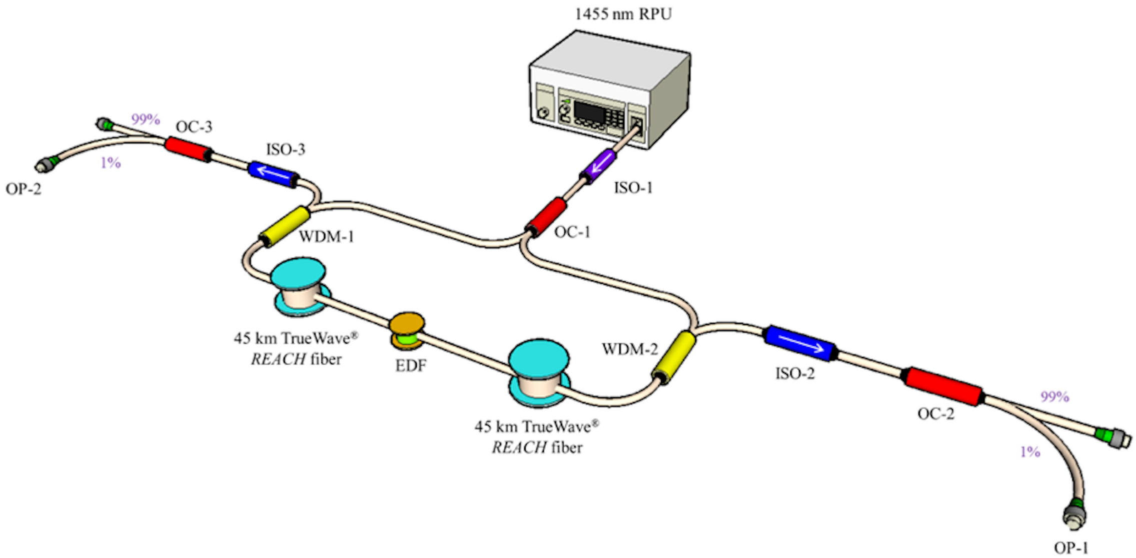

Fig. 1. Experimental setup of hybrid Raman-Erbium random fiber laser.

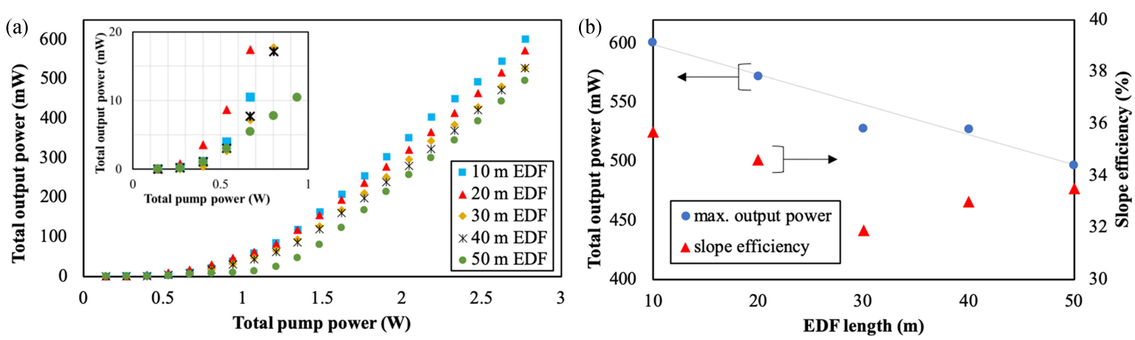

Fig. 2. (a) HRFL total power generation against total pump power variation. inset shows the detailed view of power growth from 0 W to 1.0 W. (b) Total output power and slope efficiency with respect to EDF length.

The operating principle of the HRFL scheme is based on the hybrid amplification of stimulated Raman scattering (SRS) and EDF gain in resonance with Rayleigh distributed feedback. Initially, the pump that is launched in the gain medium is converted into Raman Stokes waves generation in the TW fiber by SRS. This shifts the 1455 nm pump light by 13.2 THz, producing Raman Stokes emission in the C-band region. Upon reaching the EDF, residual pump that is unused for Raman Stokes generation excites the EDF to achieve population inversion. The self-initiated Raman Stokes emission could also serve as either a pump or signal to the EDF. Simultaneously, as the generated light propagates across the cavity, it is randomly scattered repeatedly which increases the gain of photons. The scattering event creates the 'virtual mirrors' along the laser cavity known as Rayleigh distributed feedback; a vital process to induce lasing in the random fiber laser [24].

The impact of EDF length on the HRFL power generation is presented in Fig. 2. The typical 'knee' associated with lasing threshold is difficult to determine due to the amplified spontaneous emission (ASE) noise originating from the EDF in Fig. 2(a). Therefore, the inset details the power development at a smaller scale. The range of the pump power when the HRFL reaches 5 mW power generation is from 0.45 W to 0.65 W, which is dramatically lower than random fiber lasers of similar length based on SRS alone [24]. This is made possible by the inherently low threshold to

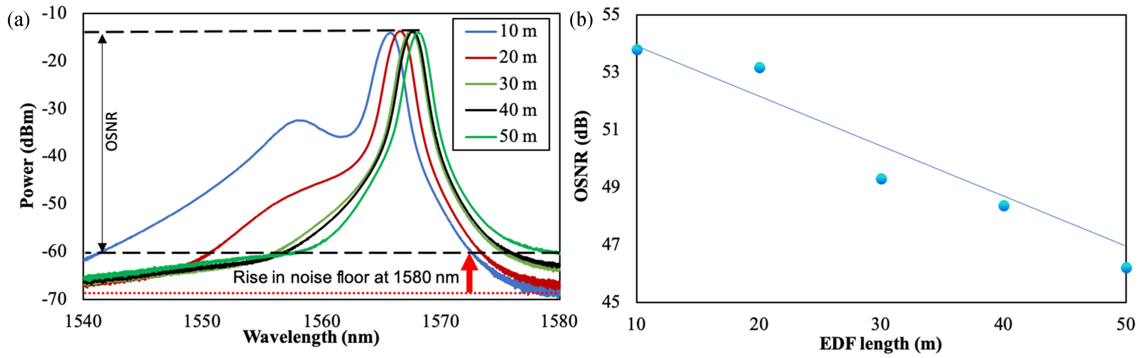

Fig. 3. (a) Optical spectrum of HRFL and (b) the OSNR with respect to EDF length at maximum pump power of 2.78 W.

excite EDF. In Fig. 2(b), the employment of 10 m EDF obtained the highest total power generation (600 mW) followed by 20 m, 30 m, 40 m and 50 m. It is no surprise that the generated power is inversely proportional to the length [see Fig. 2(b)]. With longer EDF lengths, more power is needed to achieve population inversion along the fiber length. In terms of slope efficiency, the employment of 10 m EDF also acquired the highest slope efficiency of 34.6%.

Fig. 3(a) shows the optical spectrum of the HRFL at the maximum pump power taken with Yokogawa AQ6370A optical spectrum analyzer of 0.1 nm bandwidth resolution. For 10 m EDF, there are two peaks observed that correspond to the 1st Raman gain peak and 2nd Raman gain peak; at 1557.47 nm and 1566.19 nm, respectively. Meanwhile, for the other EDF lengths, only a single peak is observed, residing within the 2nd Raman gain peak at approximately 1567 nm. With increasing EDF length, it can be observed that the dominant lasing wavelength shifts towards the longer wavelength together with suppression of the 1557 nm region. This suggests that the additional increase in EDF length is sustained by the 1557 nm emission through reabsorption, which results in the shifting of the net gain profile towards longer wavelength. The measurement of optical signal to noise ratio (OSNR) decreases linearly with longer EDF as portrayed in Fig. 3(b). This is contributed by the increase in noise floor with longer EDF lengths.

3. Wavelength-Controllable Hybrid Raman-Erbium Random Fiber Laser

Based on result analysis thus far, 10 m EDF has generated the best output power, laser slope efficiency and OSNR. Therefore, further investigation is conducted using this parameter. The optical spectrum of the HRFL with pump power variation is acquired with 0.02 nm bandwidth resolution. Fig. 4 presents the spectral development with respect to pump power at various angles in wavelength span from 1540 nm to 1580 nm as shown.

The spectral behavior of the HRFL can be divided into three regions, as R1, R2 and R3. R1 demonstrates the behavior of the laser at low power up to the initiation of hybrid lasing from 0.15 W to 0.55 W pump power. In this region, the spectral profile is simply a broadband. However, at 0.60 W, stochastic peaks appear at approximately 1550–1560 nm wavelength. At this point, hybrid amplification of EDF and Raman has been initiated in the lasing cavity.

Next, region R2 shows the onset of chaotic emission up to stable emission from 0.60 W to 1.85 W pump power. In this region, chaotic emission is manifested by the abundant fluctuating spectral spikes that appear at random wavelengths, at random intensities, and vary in time. The stochastic spectral spikes not only appear on top of the dominant gain wavelengths but also at other wavelengths. The chaotic emission is rather preeminent compared to what has been presented in previous hybrid Raman-erbium random fiber lasers [34], [35]. This effect could be an interplay between the gain-competing modes [36], [37] between EDF and higher Raman amplification provided

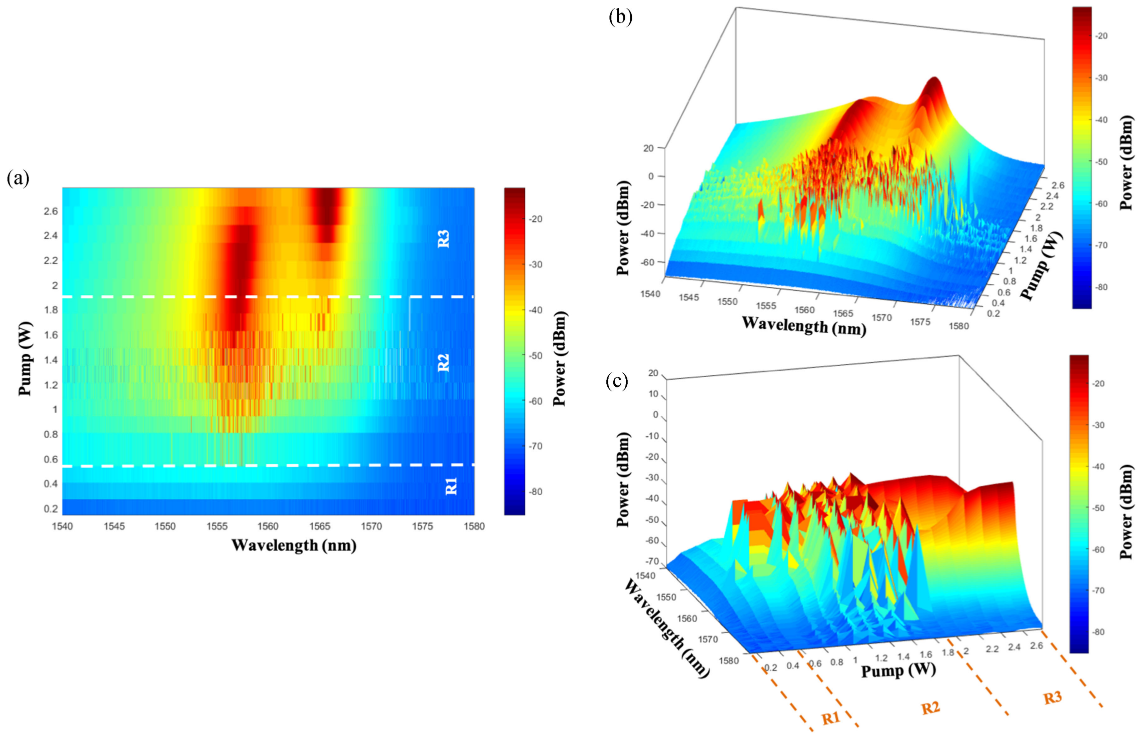

Fig. 4. The optical spectrum of HRFL as a function of pump power in (a) top view and (b) (c) 3D views with 0.02 nm bandwidth resolution.

by the TW. At pump power 1.90 W, the chaotic emission diminishes leaving behind two prominent peaks originating from the Raman gain profile, at wavelengths 1557 nm and 1567 nm.

From 1.90 W to 2.78 W pump power in region R3, stable emission is manifested by the HRFL with controllable-wavelength operation between the 1st ($\lambda 1 = 1557$ nm) and the 2nd gain peak ($\lambda 2 = 1567$ nm), and at some pump powers, both peaks exist together.

Examining region R3 in detail, the spectral output as a function of pump power is plotted in Fig. 5. It can be observed that the 2nd gain peak develops with increasing pump power. At 2.33 W, dual-wavelength operation is attained from the minimal discrepancy between the peak powers. Further increasing the pump power results in the suppression of the 1st gain peak in conjunction to the growth of the 2nd gain peak. The peak powers of each gain peak and the best differences for single and dual-wavelength operation are plotted as function of pump power in Fig. 6. For single wavelength operation, the best distinction for 1557 nm wavelength operation is 16.2 dB, while the best distinction for 1567 nm wavelength operation is 18.3 dB. For dual-wavelength operation, the peak discrepancy is only 0.1 dB.

The wavelength-controllable operation is the manifestation of the redshift phenomenon, whereby lasing modes are shifted to longer wavelengths from the increment of pump power. Commonly observed in fiber lasers operating at high intensity, this phenomenon is a product of variation in the refractive index caused by thermal expansion, shifting the lasing wavelength [38], [39]. However, in the case of the HRFL, there are a few possible explanations for the redshift effect apart from the temperature factor. The higher pump power supplied increases the gain within the cavity which allows for photons to propagate further. A longer path length within the random lasing gain medium can facilitate the reabsorption and reemission of the photons, therefore causing the redshift effect [40]. Another aspect to consider is the employment of the EDF itself. The short well-inverted EDF length has granted additional gain with minimal impact towards intracavity loss, but this also comes with higher spontaneous emission that can lead to self-saturation [41]. Taking into account the

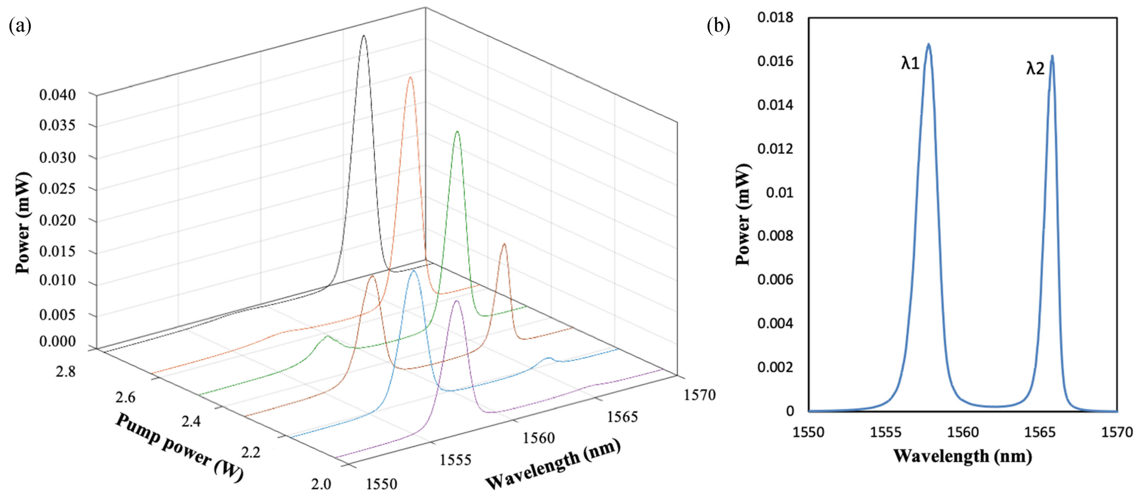

Fig. 5. HRFL spectral output (a) in region R3 with respect to pump power (b) and dual-wavelength operation at 2.33 W pump power.

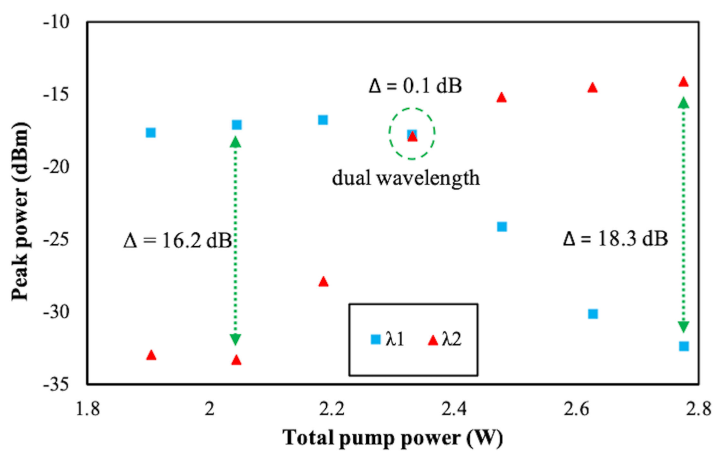

Fig. 6. HRFL 1st and 2nd gain peak powers (λ1, λ2) as a function of total pump power. The values indicated in the plot refer to the peak power difference at the best single wavelength and dual wavelength operation.

profile of the EDF in the 1540–1580 nm region, the absorption coefficient decreases with increasing wavelength, which means that the 1st gain peak wavelength is more likely to saturate earlier than the 2nd gain peak wavelength. Accordingly, the detrimental effects associated with saturation which are noise increment and gain depletion can be seen to occur on the 1st gain peak with the increase of pump power. Ultimately, this shifts the net gain profile towards the longer wavelength, which puts the 2nd gain peak wavelength at an advantage, hence supporting the peak growth.

4. Conclusion

All in all, a simple controllable dual-wavelength random fiber laser via pump power control is demonstrated. The impact of EDF length on the hybrid laser was first investigated to determine the length with the highest efficiency and output power. The HRFL with the determined EDF length was then further examined to observe its behavior, revealing a controllable dual-wavelength random fiber laser. This is the first investigation of a wavelength-controllable laser based on random distributed feedback without incorporating any selective wavelength elements. The key principle behind the laser operation lies within controlling the Raman generation via EDF gain broadening and saturation to produce dual-wavelength lasing and also induce red-shifting for single wavelength operation. The hybrid amplification between Raman and erbium via bidirectional pumping scheme also allows for a good distribution of gain across the cavity length to support this phenomenon. The best peak discrepancy for single wavelength operation is 18.3 dB while the best peak discrepancy for dual wavelength operation is only 0.1 dB. The controllable dual-wavelength random fiber laser is useful as a simple conventional single or dual wavelength fiber laser source. This study could also open up opportunities for simplified remote-based single-wavelength sensors, self-mixing interferometry-based applications, or a combination of both.

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