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Hybrid Raman-erbium Random Fiber Laser with Symmetrical Combined Pumping of 1455 nm and 1497 nm Wavelengths

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***Abstract*— This paper demonstrates an 80 km random fiber laser with and without the integration erbium-doped fiber (EDF). The scheme employs combined pumping wavelength scheme of 1455 nm and 1497 nm where variation in power of both pumps are performed and its corresponding optical spectral output is analyzed. Two broad Raman peaks at 1567 nm and 1597 nm is exhibited in the scheme without EDF due to the superpositioning of Raman spectral profiles. With the integration of EDF, the net gain profile is higher in the L-band as the 1497 nm pump emission is at an advantage from gain tilt effect.**

Keywords— fiber laser; stimulated Raman scattering; random fiber laser; random distributed feedback.

I. INTRODUCTION

In 2009, the first investigation that proved Rayleigh scattering based random feedback is sufficient to provide lasing was executed in a ~270 km ultra-long Raman fiber laser [1]. It was pointed out that the threshold of the fiber laser with random feedback is lower than the corresponding scheme utilizing FBG-based linear cavity. This led to the invention of random distributed feedback fiber laser (RDB-FL) by Turitsyn in 2010; whereby a stationary and directional continuous wave (CW) laser with a narrow spectrum was attained by random distributed feedback provided by Raman amplified Rayleigh backscattering in SMF [2]. Not only is the architecture further simplified, the randomness of the laser opens up opportunities for new range of applications that are unexplored by conventional lasers.

This paper explores the potential of hybrid random fiber laser (HRFL) that utilizes a hybrid Raman-erbium gain medium based on the combination of two types of fiber; erbium-doped fiber (EDF) and single mode fiber. This type of scheme has been deployed before [3]–[5] but has only employed a 1455 nm pump to cater for both Raman and erbium gains. This paper investigates the HRFL with a different type of pumping scheme, using two pumps of different wavelengths; 1497 nm and 1455 nm. This method is tested to examine whether it will amplify the peak centering near 1595 nm, which lacked gain without adjustments in the cavity [4]. As both pumps work simultaneously and not in a cascaded operation due to the combined symmetrical pumping, it will be intriguing to observe how the photons will interact in the presence of EDF gain and Rayleigh distributed feedback.

II. EXPERIMENTAL SETUP

The HRFL cavity is composed of 50 m LSL EDF sandwiched in between 80 km of SMF-28e fiber and employs two Raman pump units (RPU) of different wavelengths; 1497 nm and 1455 nm as shown in Figure 1. The absorption coefficient of LSL EDF at 1497 nm is 8 dB/m compared to 1455 nm pump wavelength of only 3 dB/m. Isolators are inserted just before the outputs to prevent Fresnel reflection and to ensure that optical feedback is solely from Rayleigh scattering. This open-ended configuration is symmetrical as both pumps are combined and then divided equally by the combiner and the 3 dB power coupler. Hence, only one side of the output will be used to show the spectrum. According to the manufacturer’s specifications, the two-channel combiner is designed to combine 1455 nm and 1495 nm channels into one port. The result of the combiner characterization is shown in Figure 2 where the insertion loss is measured to be 1.57 dB and 0.63 dB at 1455 nm and 1497 nm, respectively.

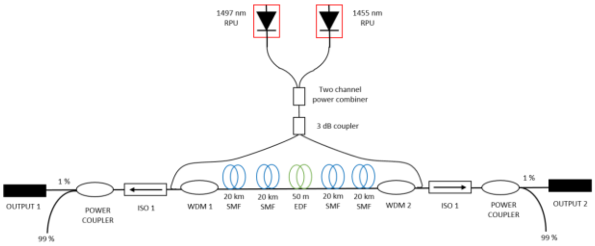

Fig. 1. *Experimental setup of HRFL with combined wavelength pumping scheme of 1497 and 1455 nm.*

Typically, the 1497 nm RPU is targeted for L-band amplification and laser operation. This is simply explained by SRS effect which converts the photons to a lower frequency by 13.2 THz, yielding Raman spectral profile within the L-band proximity with the highest peak at 1603 nm in telecommunication optical fiber. However, the combination of both pumps in the

HRFL will produce two Raman conversions which will result in spectral profiles overlapping in the C-band and L-band.

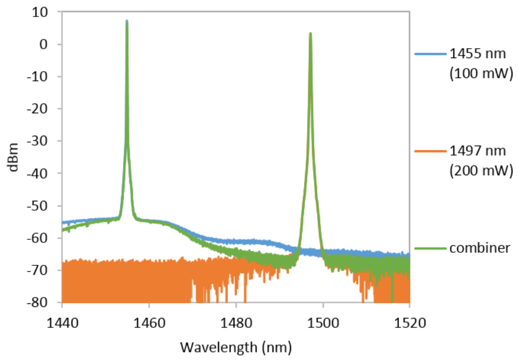

Fig. 2. *Two channel power combiner characterization. 1455 nm and 1497 nm wavelength pump is used with their respective powers shown in bracket.*

III. COMBINED PUMPING ON HYRBID SCHEME

The results of the enhanced pumping scheme are shown in Figure 3. The legend that comes with each spectrum shows the power of the 1455 nm/1497 nm pump. For example, 5.25/0.20 W legend shown in Figure 3(b) denotes 5.20 W from 1455 nm pump and 0.20 W from 1497 nm pump. The results can be divided into two parts; the first where the 1455 nm pump is fixed at its maximum power while the 1497 nm pump power is varied (see Figure 3(a)-(c)), and the second part where the 1497 nm is fixed at its maximum pump power while the 1455 nm pump power is varied (see Figure 3(d)-(f)). Results in Figure 3(a) and 3(d) do not represent the scheme because only one of the pump is used, but is included to ease the explanation. The results in Figure 3(b) show that a small power contribution from the 1497 nm is enough to set the entire operation of the HRFL to the L-band, diminishing the peak at 1565 nm. The dual-peak has evolved into a single peak centering at 1595 nm. The 1497 nm pump wavelength is amplified by the 1455 nm pump wavelength, which reduces gain available in the C-band region and disrupts the dual peak profile acquired earlier. Subsequently, increasing the 1497 nm pump to its maximum, further shifted the gain profile to 1600 nm region where a single peak at 1614 nm with a left side band composed of stochastic peaks is exhibited in Figure 3(c). The shifting of the gain profile to the 1600 nm region is caused by the Raman-induced gain tilt effect that occurs when shorter signal wavelength amplified the longer signal wavelength. Resultantly, most of the gain in the intended shorter wavelength region is depleted, which is similar to the performance limitation in conventional Raman fiber laser [6].

When the 1455 nm pump is switched off, the spectral profile product in Figure 3(d) shows the gain from EDF and Raman Stokes emission. In this situation, the residual pump that excites the EDF is no longer from the 1455 nm pump but the 1497 nm. The change of the excitation wavelength for the EDF did not change the gain bandwidth of the EDF very much. The gain from the EDF overlaps to some extent with the Raman Stokes emission, producing a wider bandwidth. The EDF gain is indicated by the presence of the slight 1530 nm peak, which is the typical emission profile of EDF. The dominant wavelength at 1603 nm corresponds to the Raman gain peak, which is 13.2 THz away from the 1497 nm pumping wavelength.

The gain tilt effect is more apparent when the longer wavelength pump is set to a higher power than the shorter pump wavelength. This can be observed when the powers of the pumps are reversed, where the 1497 nm is set to its maximum power while the 1455 nm pump is varied up to 2 W, as exhibited in Figure 3(e)-(f). The hybrid spectral profile remains centered at 1603 nm wavelength and the increase in power of the 1455 nm broadens the 1603 peak, while continually depleting the gain in the 1550 nm region. The gain tilt effect also decreases the likelihood of the 1555-1565 nm peak to appear due to insufficient gain which results in a smooth and broad, almost ASE-like spectral profile despite the high pump power that is supplied.

From the results in Figure 3, it can be ratified that the addition of 1497 nm pump to the hybrid scheme via a power combiner failed to amplify the 1595 nm peak while retaining the 1565 peak. The Raman excitation by both pump wavelengths occur simultaneously, generating random modes with random peaks within their respective Raman amplification region. The random modes are backscattered repeatedly due to Rayleigh distributed effect while competing for gain in

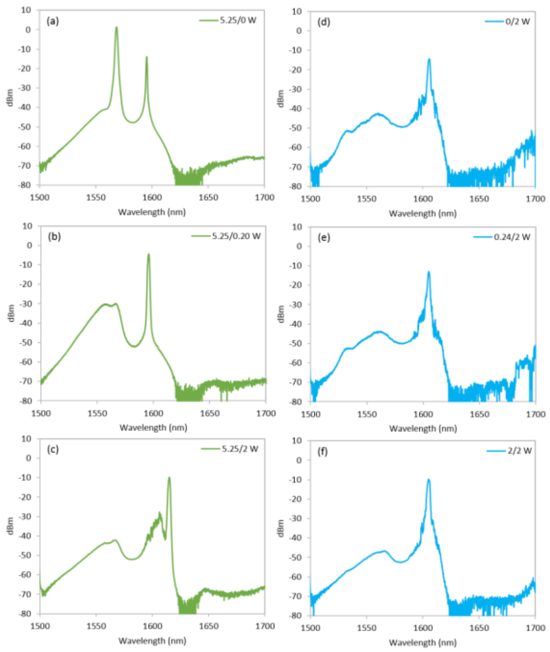

Fig. 3. *Spectral results of HRFL with combined 1455 nm/1497 nm pumping scheme with variation in power.*

the fiber gain medium. Due to the gain tilt effect, more gain is available in the longer wavelength region as the longer wavelength pump is also within the amplification territory of the shorter wavelength pump. Modes that acquire higher gain from the longer wavelength will have stronger resonance compared to modes with lower gain. Once hybrid amplification overcomes intracavity losses, the stronger resonant modes reach threshold condition, foreshadowing the dominant lasing wavelength of the spectral emission [7]. Accordingly, without a sufficiently high power from the 1455 nm pump against the 1497 nm pump, minimal laser action is present at the shorter wavelength. Thus, dual lasing operation is impossible with this current scheme regardless of the power ratio splitting between them.

IV. IMPACT OF ERBIUM-DOPED FIBER

With the presence of both Raman pumps, achieving a spectral profile that has two peaks is definitely possible as the Raman spectral profile of each pump will overlap. Superpositioning the spectral profiles of the pumps will yield an extended Raman broadband with two peaks at the highest Raman gain; 1555 nm from the 1455 nm pump and 1603 nm from the 1497 nm pump. Therefore, it remains a question whether the EDF gain played any role at all in improving the performance of the hybrid laser in gaining dual wavelength lasing. The dual peaks failed to emerge in the presence of the 1497 nm pump. Due to the low emission coefficient of EDF in the 1600 nm region, it is suspected that the effect of the EDF gain is minimal to the spectral narrowing of the HRFL. To test this, the EDF is removed from the configuration. The 1497 nm is fixed at its maximum power of 2 W while the 1455 nm pump is varied in power. The results are shown in Figure 4.

Starting with the lowest 1455 nm pump power up to 0.57 W, the spectral profile only shows a Raman broadband gain with peak wavelength of 1602 nm originating from the 1497 nm pump. Increasing the 1455 nm pump beyond 0.57 W forms a slightly raised sideband on the left of the broadband, originating from the SRS effect of the 1455 nm pump. With more power from the 1455 nm pump, the sideband prospers into a broad peak with wavelength of 1567 nm. On the other hand, the 1603 nm peak drifts towards shorter wavelength. At the maximum power of both pumps, the final wavelength of both peaks at the maximum pump power are 1567 nm and 1597 nm. The power increment from the 1455 nm pump contributed to the increase in gain at the 1595 nm region, causing the peak drifting. Imposed by the gain product of both pumps, the 1597 nm peak is higher than the 1567 nm peak. The presumption that two peaks will form due to the superpositioning is legitimate. However, the peaks are broad; tallying to the Raman gain profile, which show no signs of spectral narrowing (one of the indicators that the system is approaching laser threshold) within the available pump power.

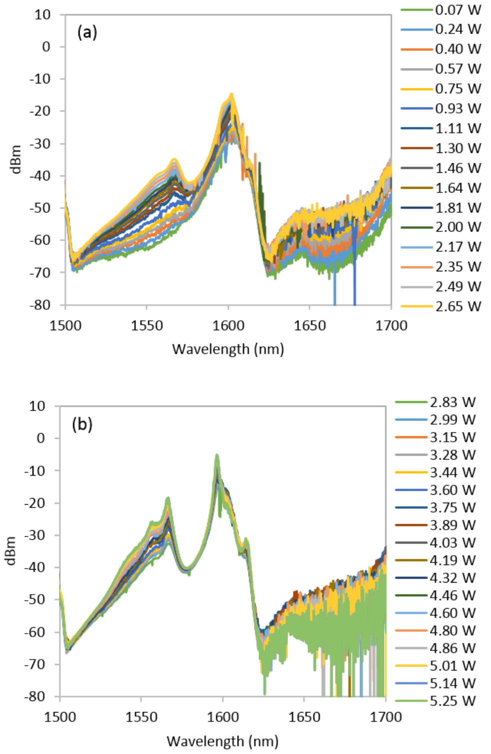

Fig. 4. *Results of RDB-FL with combined 1455 nm/1497 nm pumping scheme. 1497 nm pump is used at maximum power of 2 W while 1455 nm pump is varied in power.*

To confirm the impact of the EDF in the hybrid gain scheme, spectral output comparison with and without EDF integration at the maximum pump power for both pumps is shown in Figure 5. As described earlier, two broad Raman peaks at 1567 nm and 1597 nm is exhibited in the scheme without EDF. When EDF is integrated into the system, the net gain profile is higher in the L-band because the 1497 nm Raman pump emission is at an advantage from the gain tilt effect. This is manifested by the 1st and 2nd Raman gain peak (at wavelength 1605 nm and 1615 nm, respectively) and a spectrally flattened region in the 1555-1565 nm wavelength. The 1605 nm peak is broad and composed of stochastic peaks due to the competition between the Raman emission of the 1455 nm and 1497 nm pump that overlaps in that region. On the other hand, the 1615 nm peak is tall and narrow due to the lack of competition from the emission of 1455 pump and also from the assistance of EDF. Prior to the integration, a narrow peak was not attainable even at the highest pump powers. Once again, this shows that despite the short length of EDF, it has a huge impact on the HRFL performance. It is also observed that the residual pump from both pumps are smaller with the integration of EDF, confirming that EDF utilizes both residual pumps for population inversion. Meanwhile, the lower 2nd order Raman

Stokes corresponds to the lower integral of the 1st order Stokes from the 1455 nm pump.

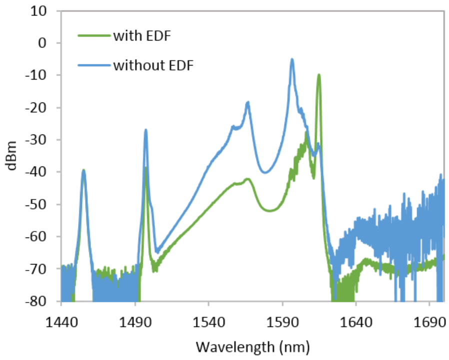

Fig. 5. *Comparison of RDB-FL with and without the integration of EDF with similar pumping scheme and pump power (5.25/2 W for 1455/1497 nm pump).*

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