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Single-pump multiwavelength hybrid Raman-EDF laser using a non-adiabatic microfiber interferometer

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ABSTRACT

This paper presents a multiwavelength fiber laser utilizing non-adiabatic tapered EDF based Mach Zehnder Interferometer (MZI) in hybrid Raman-EDF gains design with a linear cavity. A stable laser was obtained from the single pump with a 1497 nm wavelength through the employment of a 20:80 optical circulators and 99% reflective mirror. The generated backward propagating oscillates inside the laser cavity generate the stable multiwavelength output with 4 channels, which is coupled out via the 10:90 coupler and the output laser is characterized using an OSA with a resolution of 0.015 nm. The hybrid Raman-EDF gain is pumped from the external cavity by a Raman Pump Unit (RPU) and produced a stable multiwavelength laser output with SMSR of 28.9 dBm for 300 mW pump power, 30.7 dBm for 1000 mW pump power and 33.7 dBm for 1500 mW pump power.

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1. INTRODUCTION

Optical fiber technology was designed not only for optical communication, but other applications including sensor system [1], navigation system [2], manufacturing [3] and many more. The role of optical fibers in other fields has stirred research in the photonics and laser technology. Before the invention of laser, the light emitting diode (LED) is used as the transmitter, but due to the increase of the data capacity, LED is no longer an ideal transmitter since its broad spectrum limits the ability to increase the transmission capacity [4]. Therefore, the laser is an ideal solution due to its narrow linewidth, high output power, compatibility to optical to electrical conversion and availability in various frequencies [5]. Laser can be found in many forms such as semiconductor laser, gas laser and optical fiber laser [6, 7]. Among all, optical fiber laser has numerous advantages including ultra-narrow emission spectrum and high output power that is particularly useful especially for high accuracy technologies [5].

As part of optical fiber laser, multiwavelength fiber laser also generates interest, especially towards improving the wavelength division multiplexing (WDM) system. These lasers also have a large potential in the fiber-optic test and measurement of WDM components. There is work reported on fiber laser using the effect of Stimulated Brillouin Scattering [8]. However, Brillouin effects requires high pump power to achieve threshold conditions for lasing. The fundamentals for such multiwavelength optical sources are: a high number of channels over the large wavelength span, moderate output powers per channel with a good optical signal to interference ratio (OSNR) and spectral flatness, single longitudinal mode operation of each laser line and accurate placement on the frequency grid [9, 10]. Accomplishing all these requirements simultaneously is a difficult task, and many different approaches using semiconductor or Erbium-Doped Fiber (EDF) technology has been proposed and tried out in order to obtain multiwavelength laser oscillation [11].

Nevertheless, an intrinsic disadvantage of EDF is it possesses a strong homogenous line broadening and cross-saturation gain at room temperature [12, 13]. In this experiment, a multi-wavelength fiber laser based on a hybrid gain medium of EDF and Raman has been introduced to suppress the homogenous line broadening of Erbium ions and able to operate in several wavelength regions; C band and L. This region has attracted the most attention because it coincides with the low loss region of silica fibers used for optical communications.

To produce a multiwavelength laser output, an interferometer is required within the laser cavity. An interferometer is a technique that employs the superposition of electromagnetic waves [14]. There are a number of categories in utilizing this technique, which differ in terms of the properties that includes the properties of EM waves, the propagation path and also the method of splitting and combining the waves [14]. One of the methods of interferometer technique if the splitting involving only the amplitude waves, it called as amplitude splitting; such as Mach Zehnder interferometer (MZI), Fabry Perot and Michelson interferometer [15, 16]. The technique is different with the splitting of wave front such as Young slit experiment and also Lloyd mirror. Generating multiwavelength fiber laser utilizing both techniques has been demonstrated through various experiments [15, 16].

The major drawbacks of these methods are the high losses introduced by integrating the interferometer inside the cavity. Besides, the physical construction of the techniques is challenging. Hence, this work introduced tapered EDF based on Mach Zehnder interferometer. In this work, the fiber acts as an MZI as well as amplification element in the cavity as a section of EDF is tapered. The tapered EDF based MZI can be physically understood as an interferometer. The selection of this technique is based on its advantages including; easy to fabricate, compactness, low cost, low loss and possibility for future implementation.

2. RESEARCH METHOD

A schematic diagram of the multiwavelength fiber laser is shown in Figure 1. The operation of multiwavelength laser started when 1497nm Raman Pump Unit (RPU) with 0.2 W - 1.8 W pump power respectively get associated with 10%, 20, 30%, 40%, 50%, 60%, 70%, 80% and 90% coupler to produce a laser spectrum in the Raman-EDF gains medium. The variety of coupler allow the pump wavelength to enter the fiber transmission system without disturbing the signal when Raman pump spliced into the laser transmission system. The RPU continually pumps the fiber and as pulses pass through the system, they are amplified through the hybrid Raman-EDF medium while the pump light is depleted.

RPU are based on stimulated Raman scattering, which occurs in fibers at high powers. When pumping is direct to the upper laser state, the lowest lying level experience rapid relaxation from which laser action is produced [17]. In this case, the laser output occur in the region of 1510 nm - 1630 nm consequently. The higher levels of that state are not significantly populated and hence can serve as a lower level of population inversion. The population then rapidly decays to the lower level at that state [18].

As illustrated in the Figure 1, a section of SMF with a distance of 11 km and 17 m EDF is used to form a hybrid Raman-EDF cavity to produce a stable laser output. For a signal wavelength at 1597 nm, the pump wavelength should be about 1497 nm to ensure the highest gain. To achieve a gain flatness over a broad range of signal frequencies, multiple pumping mechanism are usually used in practical systems. For example, the variety number of coupler will produce a forward and backward pumping mechanism with the result of different type of gain medium produced [19].

To achieve this laser it is necessary to contain photons within the laser medium and maintain the conditions for coherence [20]. This is accomplished by placing mirrors and circulator at either end of the amplifying medium, as illustrated in Figure 1. The optical cavity formed is more analogous to an oscillator than an amplifier as it provides positive feedback of the photons by reflection at the mirrors and circulator at the end of the cavity. Hence the optical signal is fed back many times while receiving amplification as it passes through the Hybrid Raman-EDF gain medium. Although the amplification of the signal from a single pass through the medium is quite small, after multiple passes the net gain can be large. A stable output is obtained at saturation when the optical gain is exactly matched by the losses incurred in the amplifying medium. In addition, the performance and of the laser will be discussed further in this paper in term of stability, output power, SMSR, lasing threshold, spectral spacing and line width.

In this experiment, single-mode fibers were tapered to a diameter of a 10 µm (waist diameter) causing multiple cladding modes to be stimulated and to propagate through the taper waist (interference). The presence of multiple modes creates an interference pattern in the output signal. As presented in Figure 2, tapered regions serve as interference interface, [21]. The taper fiber interference spectrum analyzed in the work is obtained by the interaction between two ways the fundamental mode HE_{11} (I_1) and a HOM (High Order Mode) HE_{1m} (I_2). This modal interference is shown by the equation:

$$I = I_1 + I_2 + 2\sqrt{I_1 * I_2}\cos(\phi) \quad (1)$$

Here the phase (Φ) is the difference between the propagation constant of the modes involves and can be expressed in terms of the effective refractive index difference of both modes:

$$\phi = \frac{2\pi \triangle n L}{\lambda} \quad (2)$$

Where the difference between the effective refractive index of fundamental mode (n_1) and the HOM (n_2) is expressed by $\triangle n = n_2 - n_1$, λ is wavelength operation and L is the length of the fiber waist for the tapered fiber. The phase difference between the modes is generated when the tapered down area generated these modes and they recombine to a single mode again after the tapered-up zone.

The multi-reflection process that happen in the tapered based EDF is unique and it produces a transfer function much different from the other interferometer such as Fabry-Pérot [22, 23], Michelson and Sagnac configurations [24, 25]. The narrow core along the fiber phase is extremely high sensitivity and relatively low loss and for this reason, the tapered based EDF filter has a greater sensitivity and one of the best results to produce multiwavelength laser compared to the other techniques.

Figure 1. Schematic diagram of multiwavelength fiber laser

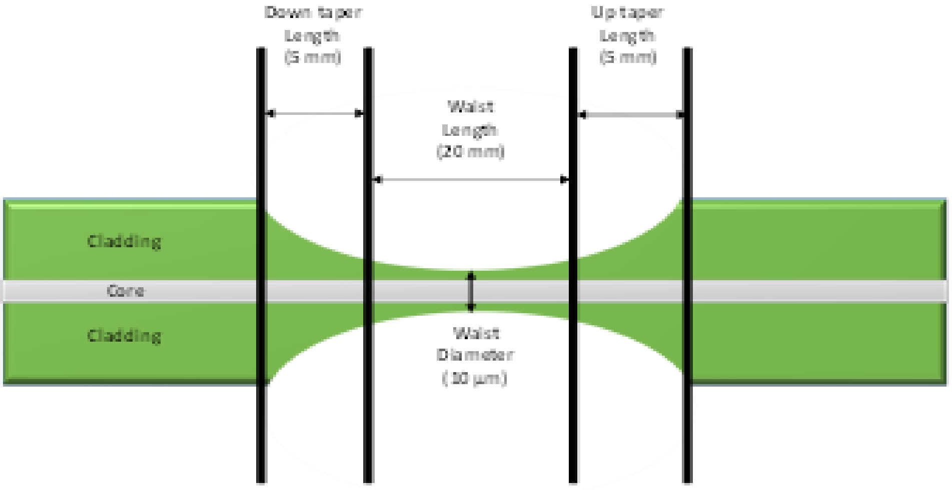


Figure 2. Tapered Single mode fiber as Mach–Zehnder Interferometer

3. RESULTS AND ANALYSIS

The transmission spectrum of the tapered fiber using the amplified spontaneous emission (ASE) source was shown in Figure 3 and the result shows the power variations are largely sinusoidal in the data. In order to determine the best result on the transmission spectrum, the taper was fixed in a flow cell trough and held in place by a silicone cement to avoid bending effects.

The low noise, broad bandwidth of Raman, and low pump power requirements of EDFAs can be combined into one hybrid amplifier to solve amplification issues in long-haul and ultra-long-haul networks. Raman amplifiers provide a gain across a large bandwidth. In contrast, EDFAs provide a substantial gain, but across a relatively small band, and the gain provided is not flat. By combining both, the spectrum achieved is much better than individual configuration.

As shown in Figure 4, a multiwavelength fiber laser based on a hybrid gain medium of Raman-EDF with 17 m EDF, 11 km SMF, 10:90 pump coupler and 300, 1000 and 1500 mW pump power have been introduced to overcome this problem. The output power of Hybrid Raman-EDF gain is higher when 1500 mW pump power was used compared 300 mW and 1000 mW. This shows the combination between these two media produces more broader gain, so they are able to accommodate more channels. Also, due to Raman amplifiers' non dependence on carrier lifetimes of meta stable states, they can be used at higher bit rates and stable at room temperature.

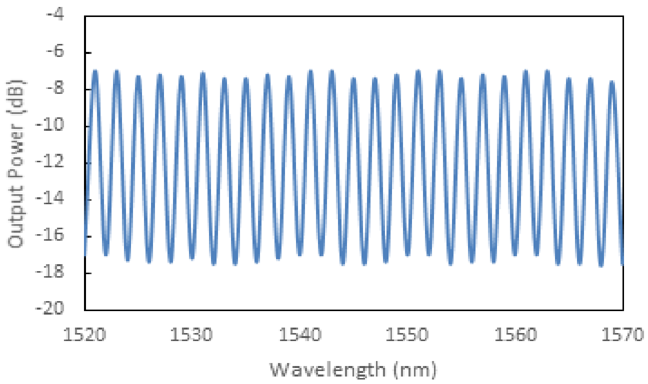


Figure 3. Transmitted laser power versus wavelength for the tapered fiber

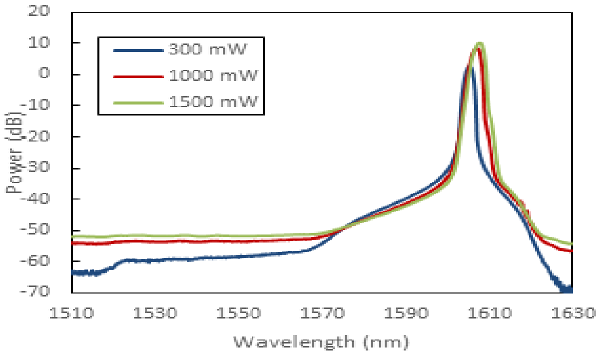


Figure 4. Fiber laser based on a hybrid gain medium of Raman-EDF with different pump power; 300 mW (blue), 1000 mW (red) and 1500 mW (green)

In order to study the multiwavelength effect on the laser, a higher Raman pump power is needed. The hybrid Raman-EDF gain is pumped from the external by RPU. Thus, in this work, a hybrid gain of Raman-EDF is used to boost the laser output power. As a result, the combination of both gains produces a stable multiwavelength with SMSR of 28.9 dBm for 300 mW pump power, 30.7 dBm for 1000 mW pump power and 33.7 dBm for 1500 mW pump power. The generated backward propagating oscillates inside the laser cavity generate the stable multiwavelength output with 4 lasing line for 300 mW pump power and 2 lasing line for 1000 mW and 1500 mW respectively. The output was coupled out via the 10:90 coupler. As shown in Table 1, by varying the pump power used, the number of lasing line, spectral spacing, SMSR and peak power also differs. This parameter is defined as the efficiency of the fiber laser to convert pump energy into lasing signal energy.

Table 1. Multiwavelength Laser Specification with 10:90 Coupling Ratio

Pump Power (mW)	Lasing line	Spectral Spacing (nm)	Line Width (nm)	SMSR (dB)	Peak Power (dBm)
300	4	3.7	0.3	28.9	-6.7
1000	2	3.9	0.3	30.7	4
1500	2	4.0	0.3	33.7	5.8

In Figure 5, the multiwavelength laser output spectrum is demonstrated by using different coupler ratios in the configuration of Figure 1 with the pump power between 0.2-1.8 W. If the total hybrid Raman-EDF gain is equal to or higher than the cavity loss, multiwavelength laser oscillation can be formed between the optical circulators and 99% reflective mirror. As shown in Figure 1, the multiwavelength laser is generated with 10:90, coupler, which contributes to higher injected power into the SMF and EDF with lower cavity loss. However, the laser cannot be generated with high efficiency when another type of coupler is applied coupler due to the injected pump power into the SMF which is lower than the threshold and the high loss in the cavity. The highest peak is obtained with a 10:90 coupler which has the lowest cavity loss. The 300 mW pump power produces a best result for multiwavelength generation. According to results obtained in Figure 5, the 4 simultaneous lines are obtained at approximately 1594.65 nm, 1598.1 nm, 1602.6 nm, and 1606.5 nm. The 1000 mW and 1500 mW power are injected to the cavity and produce 2 channels multiwavelength laser at approximately 1602.6 nm, and 1606.5 nm. The value of SMSR is increased when more power injected through the pump. This happens due to the signal propagates in the opposite direction of the cavity and travels to the circulator, acting here as a reflector, before it is rerouted back into the Raman-EDF gains in the mirror. The amplified signal, then travels back to the other side of reflector and this oscillation continues to generate the higher SMSR and also increases the output power of the laser as shown.

Laser stability is one of the important elements for a laser source. It refers to the temporal stability of the peak power and wavelength of the laser source in the condition that variation in the peak power and the wavelength of the laser source is minimized. Many factors influence a source’s stability, such as temperature, pump condition and the gain dynamics. Finally, the output stability testing of proposed single pump multiwavelength fiber laser utilizing tapered EDF based MZI in hybrid Raman-EDF gains design with a linear cavity is made to execute the output performance of power and wavelength. In this experiment, we select one of the lasing lightwave at 1606.05 nm initially for measurement. Here, the output power was observed every 5 minutes for 2 hours using an optical power meter. As shown in Figure 6 (a) and (b), the peak power and wavelength variations are measured at ±1.8 dB, ±0.3 dB, ±0.9 dB and ±0.2 nm, ±0.15 nm, ±0.1 nm for 300 mW, 1000 mW, 1500 mW pump power, respectively. Hence, the results present that the proposed multiwavelength laser has the excellent optical output stabilities for future system application. In addition, under 2 hours observing time, the measured output stabilities of the proposed laser are still maintained.

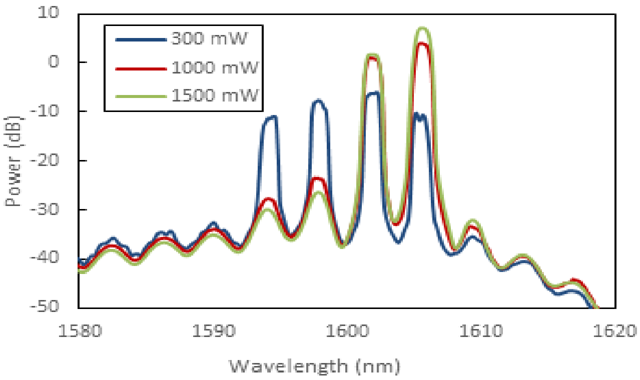
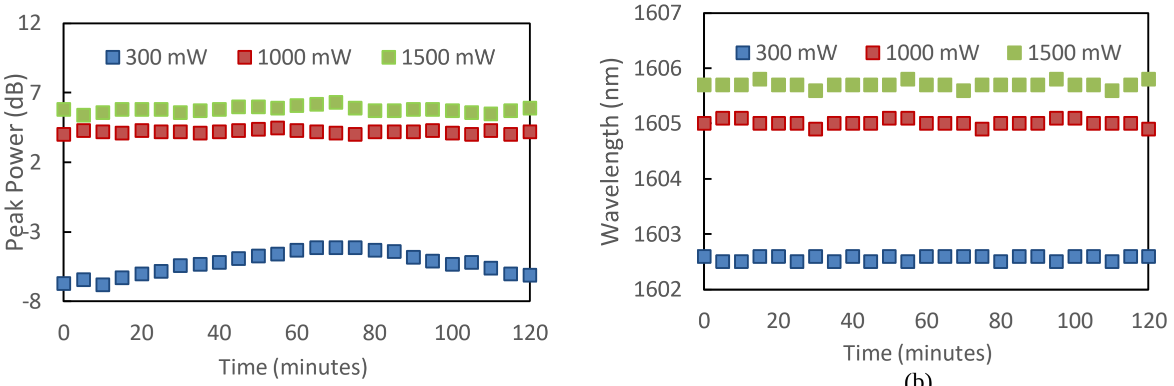


Figure 5. Multiwavelength output signal from single pump laser utilizing Tapered based MZI with 10:90 arm of an optical coupler (OC)



(a) (b)

Figure 6. Stability test of the laser with various pump power (a) Wavelength versus time and (b) Peak power versus time

An important characteristic of a pumped laser source is its slope efficiency. It is obtained by plotting the laser output power against the pump power. Above the threshold power, the curve increases linearly. The efficiency of the laser is given by the slope of this line. This characteristic is due to the same optical loss for all input powers in a cavity. However, the curve may be nonlinear especially for high power lasers, typically with lower slope at high input powers. For an optical laser source, efficiency represents the ratio of the lasing output power over the pump power, in other words, the conversion of the pump energy to the lasing energy. For example, efficiency of a 10:90 coupling ratio laser system has been reported to be about 80%. This value can be obtained from the slope of the transfer characteristic curve as shown in Figure 7.

The minimum amount of pump power required for a laser source to begin lasing is defined as the threshold power. When the pump power is below the threshold power, the output power of the laser source is incoherent and spontaneous. As shown in Figure 7, the threshold power increases as the coupler value increases from 10% to 90%. The total pump power and output power behavior is initially linear but saturates at high input signal powers. The result shows power conversion efficiency (PCE) has a maximum value when 10:90 coupler was applied.

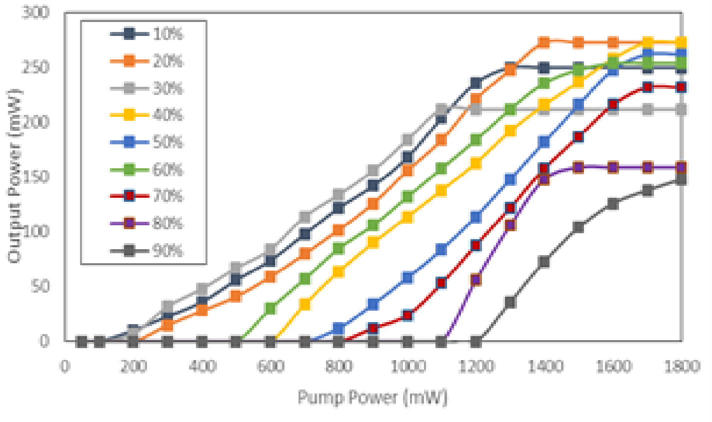


Figure 7. Threshold power graph with different coupling ratio

The interaction between hybrids Raman-EDF is also investigated in the last part of this paper. The results show that the reduction in the threshold power occurs under different Raman pumping power in a linear cavity with 11 km SMF and 17 m EDF. The threshold decreases with the increase of Raman-gain On-Off and this decrease is much faster forward pumping than for backward pumping due to the lower Raman gain at this scheme. It is revealed that the amount of threshold reduction depends strongly and solely on the gain effect on it, dependent of Raman pumping power injected to the laser cavity.

By implementing the reflective mirror at one end, it allows the lasing wavelength to pass the Raman-EDF gain twice per one oscillation and thus increases the net gain per oscillation. This results in the linear cavity to exhibit a lower threshold power and achieves larger SMSR. The proposed cavity using a hybrid Raman-EDF gain medium will allow for the development of compact multiwavelength devices.

4. CONCLUSION

This paper presents a multiwavelength laser utilizing a non-adiabatic tapered based-EDF using hybrid Raman and EDF gains in a linear cavity configuration. This tapered-based interferometer has the advantage of simplicity of the fabrications and provides low loss interferometer as compared to its counterpart. A stable output laser of 4 lines is obtained at 300 mW with SMSR of 28.9 dB and 2 lines was produced at 1000 and 1500 mW with SMSR of 30.7 and 33.7 dB respectively. The laser is very stable at room temperature with peak power variations of 0.3 to 1.8 dB and wavelength variations of 0.1 to 0.2 nm for two hours continuous operation.

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