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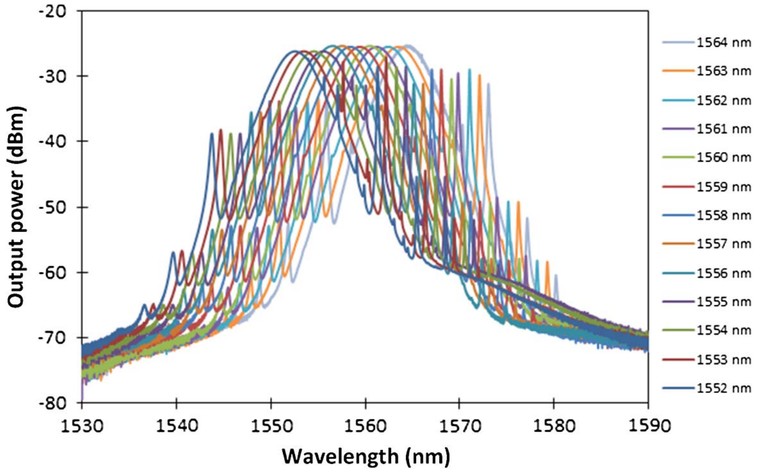

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Graphene-Based Mode-Locked Spectrum-Tunable Fiber Laser Using Mach–Zehnder Filter

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Abstract: An ultrafast spectrum-tunable fiber laser using a tunable Mach–Zehnder filter (TMZF) and a graphene-based saturable absorber as a mode-locking element is proposed and demonstrated. The proposed laser uses a 2-m-long zirconia–erbium-doped fiber (Zr-EDF) as the primary gain medium. The Zr-EDF has a dopant concentration of 3800 ppm/wt and an absorption rate of 18.3 dB/m at 980 nm. The proposed laser is able to generate mode-locked solitons, with the central wavelength of the spectrum tunable from 1551 to 1570 nm and covering a wavelength range of about 19 nm. Sidebands are observed with 3-dB bandwidths and pulsewidths of between 3.4 and 3.6 nm and from 730 to 780 fs, respectively, as well as a time–bandwidth product between 0.32 and 0.33. The generated pulse yields an average output power value of ∼1.4 mW, pulse energy of ∼128 pJ, and repetition rate of ∼10.9 MHz. This is the first time, to the knowledge of the authors, that a graphene-based mode-locked spectrum-tunable fiber laser is demonstrated using a TMZF.

Index Terms: Graphene-based saturable absorber, zirconia-based erbium-doped fiber, Mach–Zehnder filter, spectrum tunable mode-locked.

1. Introduction

The generation of simple and compact ultrafast passively mode-locked fiber laser with spectral tunability has always drawn a great attention among the researchers around the world, owing to its significance in various application fields, including telecommunications, spectroscopy, material processing, and biomedical research [1]–[6]. Compared to the active approach, the passively mode-locked fiber laser is more preferable as it is easier to be operated and does not involve the use of bulk active components which will eventually increase the complexity as well as the cost of the system. An interesting way in realizing the passively mode-locked fiber laser is by incorporating a broadband saturable absorber (SA) within the laser cavity, which is able to provide the tunability over a wide wavelength range [7]. Nowadays, graphene, a single layer atom of carbon, has been a great candidate to be applied as the SA with its desirable optical characteristics such as ultrafast recovery time [8]–[10]. With its advantage over semiconductor saturable absorber mirror (SESAM) in terms of the cost, tuning range and ease of fabrication [6], [11], graphene has been widely accepted to replace the usage of SESAM. Another carbon allotrope, called carbon nanotubes (CNT), has also been well demonstrated as the SA for mode-locking [12]–[15]. However, the operational wavelength range of CNT is quite limited due to the absence of the gapless behavior of the atomic layer as possessed by graphene.

In general, most wavelength tunable mode locked fiber lasers are demonstrated by using the tunable bandpass filter (TBF) [1], [2], considering that TBF is easily available and inexpensive. Nevertheless, the bandwidth of the TBF is quiet limited. In this regards, by employing the TBF in the soliton mode-locking regime with Kelly sidebands, the Kelly sidebands would eventually be eliminated or suppressed due to the spectral limiting effect of the filter [1], [16]. Besides that, the usage of the TBF would also restrict the bandwidth of the mode-locked spectrum which consequently increases the mode locked pulse width. Thus, it is necessary to find a right element acting as the filter while conserving the original shape of the mode locked spectrum as well as maintaining the bandwidth and the pulse width of the mode locked pulses. Tunable Mach Zehnder Filters (TMZFs) can be a useful candidate for this purpose and also a suitable alternative over the TBF to overcome the problem. Although there have already been numerous reports on graphene-based tunable mode locked fiber lasers, thus far, there are no reports on graphene based mode locked fiber lasers by using the Mach Zehnder filter as the wavelength selective mechanism. Therefore, it is still of interest to study and investigate the performance of tunable mode locked fiber laser by using the Mach Zehnder filter as the wavelength selective mechanism.

In this paper, a graphene-based mode-locked, spectrum tunable fiber laser using Mach Zehnder filter is presented. A short length of 2 m Zirconia-Erbium doped fiber (Zr-EDF) is used as the gain medium in a ring laser cavity configuration, which has an erbium ion concentration of 3800 ppm/wt and an absorption rate of 18.3 dB/m at 980 nm. Soliton mode-locking is attained, with the central wavelength of the mode locked spectrum is tunable from 1551 nm to 1570 nm, covering a wavelength range of about 19 nm. In the wavelength region in between 1552 nm and 1564 nm, the mode locked sidebands are conserved and are also being tuned together along with the tuning of the spectrum, with the 3 dB bandwidth and the pulse width having only a slight variation, from 3.4 nm to 3.6 nm and from 0.73 ps to 0.78 ps respectively across the wavelength range. The corresponding TBP values are also observed to have a small variation, which is from 0.32 to 0.33. The generated pulse yields an average output power of $\sim$1.4 mW, with the pulse energy of $\sim$128 pJ. The repetition rate is $\sim$10.9 MHz, corresponding to a pulse spacing of around 92 ns in the pulse train. To the best of our knowledge, this is the first report of the graphene-based mode-locked, spectrum tunable fiber laser using TMZF with the ability to conserve the soliton shape of the mode locked spectrum as well as maintaining the bandwidth and pulse width of the mode locked pulses within the certain wavelength region.

2. Experimental Setup

The schematic diagram of the tunable, mode-locked fiber laser is shown in Fig. 1, which consists of a 2 m long Zr-EDF which acts as the gain medium. The Zr-EDF incorporates glass modifiers and nucleating agents such as ZrO_2, Y_2O_3, Al_2O_3, Er_2O_3, and P_2O_5 in a fused silica Single Mode Fiber (SMF) which provides the necessary modification to the glass host matrix to allow for high Er_2O_3 dopant concentrations to be realized. The addition of the ZrO_2, helps to alleviate the clustering effect, thus preventing concentration quenching from occurring and optimizing the performance of the fiber [17]. The erbium dopant concentration is much higher than that of the standard erbium doped fiber (EDF) with a value of about 3880 ppm/wt. with. The Zr-EDF is pumped by a 980 nm laser diode (LD) through a 980 nm port of a fused 980/1550 nm wavelength division multiplexer (WDM) and has an absorption coefficient of 18.3 dB/m at 980 nm.

The Zr-EDF is then connected to the input port of an optical isolator as to ensure uni-directional oscillation in the clockwise direction within the ring cavity, which is then connected to a polarization controller (PC) and subsequently to a 90 : 10 fused coupler. A portion of the signal is extracted for further analysis, while the 90% is connected to the SA formed by sandwiching a thin layer of graphene between two FC/PC connectors. The graphene used to form the SA is developed from graphene flakes suspended in N-methylpyrrolidone (NMP) solution procured from Graphene Research Ltd. The average flake thickness of the graphene flakes is about 0.35 nm with an average

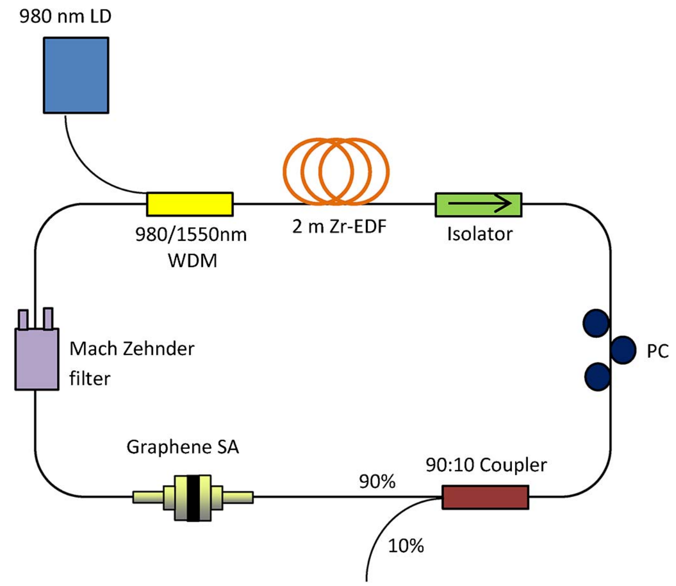
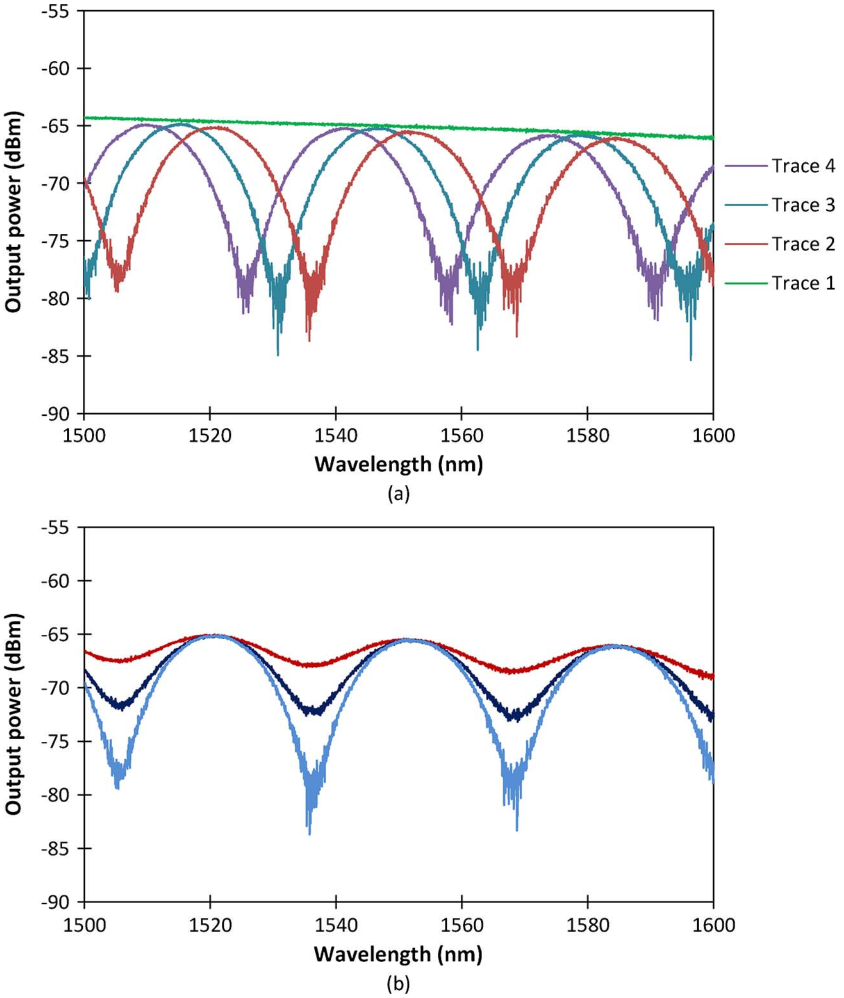


Fig. 1. Experimental setup for the tunable mode-locked fiber laser (LD: laser diode, WDM: wavelength division multiplexer, Zr-EDF: zirconia based erbium doped fiber, PC: polarization controller, SA: saturable absorber, which has a graphene layer).

particle size of 550 nm. The graphene SA is formed by first depositing the graphene layers onto the face of a fiber ferrule, using the same process as described in reference [18], before being connected to another fiber ferrule to form the SA. After passing through the graphene-based SA, the propagating signal will become a mode-locked pulse, which is then channeled through a Photonics Technologies AFL-1550-32-TU-1 TMZF. The TMZF acts as the tuning mechanism of the system, and provides either wavelength tuning or extinction ratio tuning. The output from the TMZF is then connected back to the 1550-nm port of the WDM, thereby completing the ring cavity. The total cavity length is about 17.5 m, with a total SMF length of approximately 15.5 m. The dispersion coefficient of the Zr-EDF is approximately $+28.45$ ps/nm.km [17], giving a group velocity dispersion (GVD) coefficient of $-36.86\ \text{ps}^2/\text{km}$. On the other hand, the dispersion coefficient of the SMF-28 is about $+17$ ps/nm.km, giving a GVD coefficient of $-22.02\ \text{ps}^2/\text{km}$. The total GVD for the entire cavity is $-0.415\ \text{ps}^2$, thereby putting the operation of the laser in the anomalous dispersion regime. A Yokogawa AQ6317 optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to measure the output spectrum of the generated mode-locked laser, while the mode-locked time characteristics are measured using an Alnair HAC-200 auto-correlator. A LeCroy 352A oscilloscope together with an Agilent 83440C lightwave detector is used to analyze the mode locked pulse train properties. The radio frequency spectrum of the mode locked pulses is also observed by using an Anritsu MS2683A radio frequency spectrum analyzer (RFSA).

3. Characterization of Tunable Mach Zehnder Filter

Fig. 2(a) shows the transmission spectrum of the Photonic Technologies TMZF (Model: AFL-1550-32-TU-1) using a white light source, which is inserted at the input port and the output is connected to the OSA. The loss of the TMZF is measured to be approximately 1.2 dB for a 1550 nm laser wavelength, while a TBF experiences a loss of approximately 2.0 dB under similar conditions. The TMZF consists of two tuning knobs, which are the wavelength and the extinction knobs. By adjusting these two knobs, the tuning of the filter can be achieved. For instance, Fig. 2(a) shows the output spectrum of the TMZF by turning the wavelength knob, which is indicated by Trace 2 to Trace 4. Trace 1 is the reference signal, which is the output of the white light source. Trace 2 shows the multiple peaks at 1520.4 nm, 1552.1 nm, and 1583.7 nm. Similarly, for Trace 3 and Trace 4, the



(a)

(b)

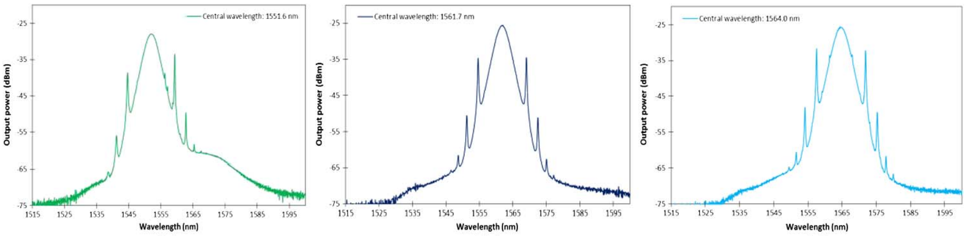
Fig. 2. Transmission spectrum of the TMZF from a white light source by adjusting the (a) wavelength knob, and (b) the extinction knob on the TMZF.

peak wavelengths are at 1514.5 nm, 1546.1 nm, 1578.0 nm and 1507.8 nm, 1539.9 nm, 1572.1 nm respectively. From this figure, it can be seen that when the knob is turned, the output peak wavelength shifted accordingly, giving the tunability, with wavelength spacing of about 32 nm between the adjacent peaks.

Fig. 2(b) on the other hand shows the transmission spectrum of when the extinction knob of the TMZF is adjusted. From the figure, it can be seen that the shape of the graph changes, with the originally shallow troughs becoming deeper as the extinction ratio knob is tuned.

4. Results and Discussion

Mode-locked pulses can be observed at a threshold pump power of about 55 mW, with the obtained optical spectrum as seen from the OSA giving a very wide-band output, together with multiple sidebands present. These sidebands confirm that the system is operating in the soliton regime. The central wavelength of the generated mode locked pulse can be tuned from between 1551 nm to 1570 nm by simultaneously adjusting the extinction ratio and the wavelength knobs of the TMZF, giving the system a tuning range of approximately 19 nm. The mode-locked spectrum is shown in Fig. 3(a)–(c), with the different transmission spectra of the TMZF obtained by adjusting the two knobs. The central wavelength of the mode locked pulses as measured from the OSA is initially



(a) (b) (c)

Fig. 3. (a) to (c) The mode-locked output spectrum as taken from the OSA for different transmission bands of the TMZF.

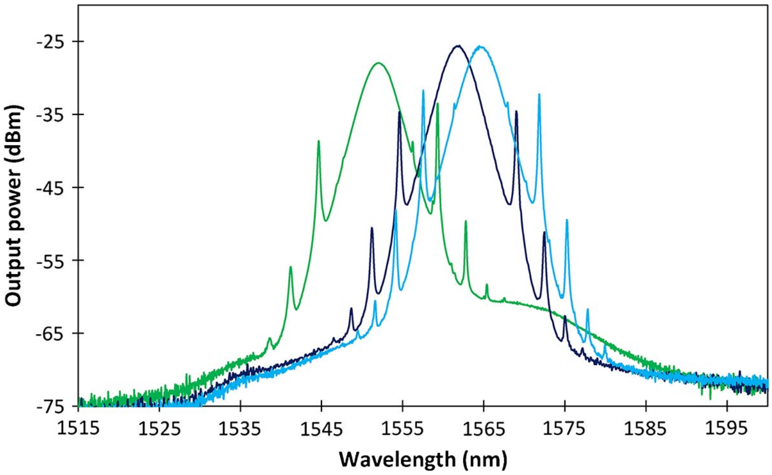


Fig. 4. The combined mode locked spectrum for different transmission bands of the TMZF.

obtained at 1551.6 nm, as shown in Fig. 3(a), while Fig. 3(b) and (c) show the central wavelengths of 1561.7 nm and 1564.0 nm that are obtained by adjusting the knobs. As can be inferred from the figure, the spectral width of Fig. 3(a)–(c) are approximately 3.5 nm, 3.6 nm, and 3.6 nm respectively.

For comparison purposes, the above spectra for different transmission bands of the TMZF are combined in a single graph as shown in Fig. 4. From this figure, it can be inferred that the peak of the output spectrum can be adjusted accordingly by the tunable filter.

Fig. 5 shows a similar profile as in Fig. 4 for a wavelength range of between 1552 nm to 1564 nm for the tuned TMZF, showing the existence of mode-locked sidebands. It can be seen that the overall shape of the mode-locked spectra remains unchanged even as the central wavelength shifts. The 3 dB bandwidth of the spectra is about 3.5 nm. It is also prudent to note that in this spectrum, Kelly's sidebands are visible, unlike tunable mode locking obtained when using a conventional TBF such as that reported in [1]. When using this TBF, no Kelly sideband structures are detected, which is a result of the filter spectral limit [16]. This will affect the time pulse width of the mode locked pulses, increasing its value.

Fig. 6 gives the autocorrelation traces of each of the different wavelength spectra in Fig. 5. The estimated pulse durations at the full-width at half maximum (FWHM) point varies between 730 to 780 fs, assuming the sech^2 pulse shape for the case of anomalous dispersion.

Fig. 7 shows the comparison of the 3 dB bandwidth, pulse width and corresponding time-bandwidth products (TBP) of the 13 different wavelength outputs obtained from the system. The 3 dB bandwidth of the spectra and the pulse width vary slightly from between 3.4 nm to 3.6 nm and 0.73 ps to 0.78 ps respectively. The TBP values show significantly less variance over the wavelength range,

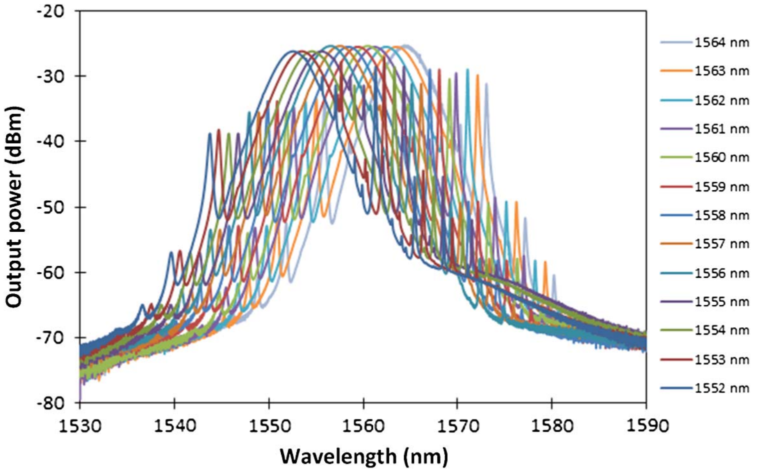


Fig. 5. Output spectra of the mode locked pulses at 13 different central wavelengths with conserved Kelly sidebands structures.

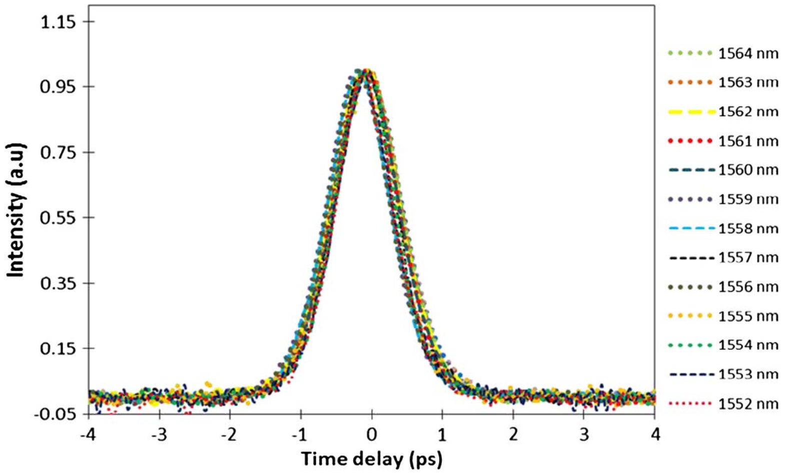


Fig. 6. Autocorrelation traces of the laser output at 13 different central wavelengths, corresponding to the central wavelengths of the output spectrum in Fig. 5.

ranging between 0.32 and 0.33 only. The TBP values are only slightly higher than the lowest value achievable for the transform-limited sech^2 pulses, which is approximately 0.315 [7]. This is attributed to the presence of minor chirping in the pulse [7], which in turn can be taken to originate from the remaining dispersion of the laser cavity [19]. This is further validated as theoretical models provide the most accurate value of the TBP as 0.315, under the condition that the transform limited sech^2 pulse can only be realized in chirp-free sech^2 pulses [12], which in reality cannot be achieved easily. Compounding this fact is the extension of the SMF, which is connected to the laser output and will cause affect the TBP value obtained [20].

Fig. 8 shows the mode-locked pulse train as obtained from the oscilloscope. The pulses are observed to have a repetition rate of about $\sim$10.9 MHz, which corresponds to a pulse spacing of about 92 ns in the time domain. The repetition rate of the pulse train is a result of the cavity length, and thus it can be predicted that shortening the cavity length will increase the repetition rate and vice-versa. Measurement of the average output power and pulse energy of the pulse yields values of approximately 1.4 mW and 128 pJ respectively.

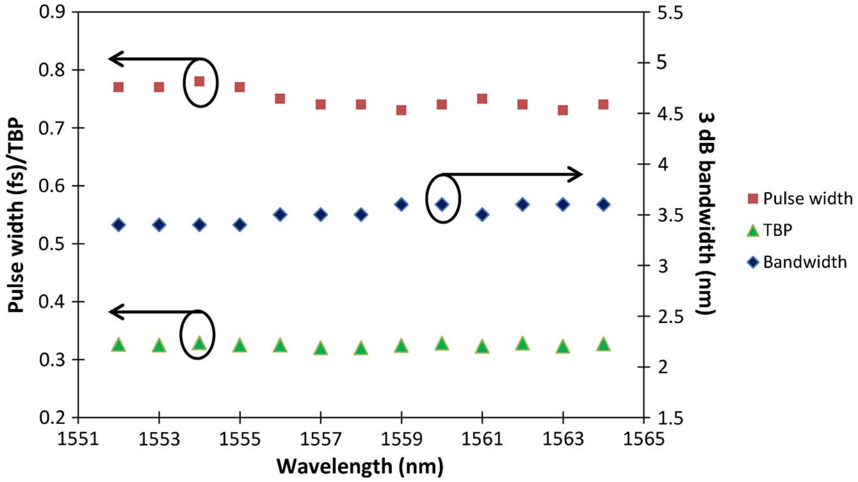


Fig. 7. Output pulse width, 3 dB bandwidth and TBP against the central wavelengths for the 13 output spectra obtained by the proposed system.

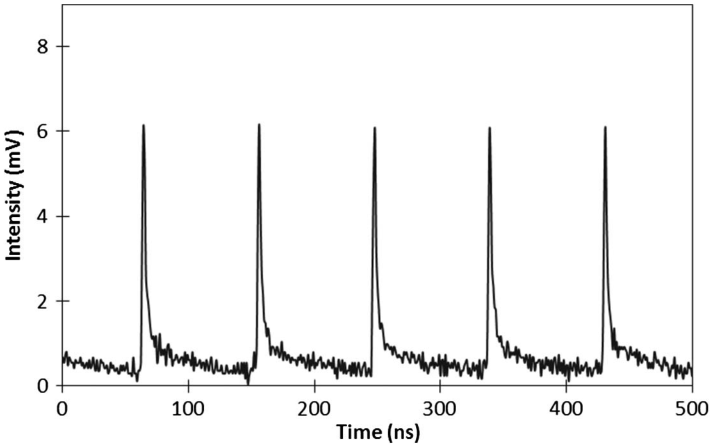


Fig. 8. Output pulse train of the mode locked pulse with a repetition rate of 10.9 MHz.

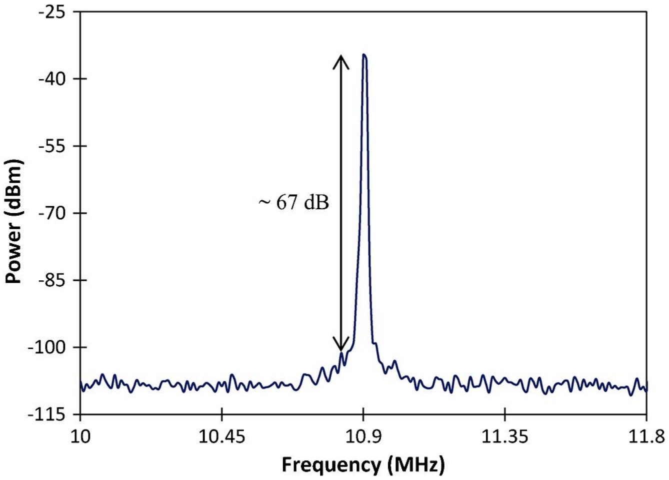


Fig. 9. RF spectrum at the fundamental repetition rate of 10.9 MHz with 300 Hz resolution.

The RF spectrum of mode-locked laser output is obtained at a repetition rate of 10.9 MHz at a resolution of 300 Hz. The measured RF spectrum indicates that the mode-locked laser output works in its fundamental regime, with an estimated peak-to-background ratio being about 67 dB, as shown in Fig. 9. This is an important factor, as it implies low amplitude noise fluctuations, good mode-locking stability as well as low timing jitter [21], [22].

Compared to previously reported graphene mode-locked tunable fiber lasers [1], [2], [23], the proposed system provides higher stability as the operating wavelength region is tuned, with lower deviations 0.2 nm, 0.05 ps, and 0.016 of the bandwidth, pulse width as well as the TBP respectively. This allows the proposed system to have significant applications where a stable pulse output is required with tunability across a wide wavelength range, such as in sensing and communication.

5. Conclusion

A graphene-based mode-locked, spectrum tunable fiber laser using TMZF filter is proposed and demonstrated. The proposed laser uses a 2 m long Zr-EDF with an active ion concentration of 3800 ppm/wt and an absorption rate of 18.3 dB/m at 980 nm as the gain medium. Soliton mode-locking is attained, with the central wavelength of the mode locked spectrum tunable from 1551 nm to 1570 nm and covering a wavelength range of about 19 nm. Mode locked sidebands are observed with the 3 dB bandwidth and the pulse width having only slight variations of between 3.4 nm to 3.6 nm and from 0.73 ps to 0.78 ps, respectively. The TBP vary between 0.32 to 0.33. The generated pulse yields an average output power of ∼1.4 mW, with the pulse energy of ∼128 pJ and repetition rate of ∼10.9 MHz. To the best of our knowledge, this is the first report of the graphene-based mode-locked, spectrum tunable fiber laser using a TMZF.

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