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Ultrafast mode-locked dual-wavelength thulium-doped fiber laser using a Mach-Zehnder interferometric filter

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ABSTRACT

A simple and robust method to generate a dual-wavelength mode-locked laser using a tunable Mach-Zehnder filter (TMZF) and a single-wall carbon nanotube (SWCNT) based saturable absorber (SA) is proposed and demonstrated. The proposed laser uses a thulium-doped fiber for lasing in the two-micron region and exploits the interferometric spectrum of the TMZF to produce dual peaks with nearly equal magnitude. SWCNT based SA enables mode-locking at a threshold value of 150.4 mW with distinct dual-wavelength peaks at 1919.2 nm and 1963.7 nm. The peaks have a calculated pulse width of 1.8 ps and 1.6 ps, respectively with a repetition rate of 9.1 MHz with a relatively high optical-signal-to-noise ratio value of 59.1 dB. The output is also observed to remain unchanged over time, indicating high stability. The proposed laser has a promising application, particularly in ultrafast gas molecular spectroscopy and sensing.

1. Introduction

Single-wavelength ultrafast pulsed laser sources have been extensively studied due to their potential for a multitude of applications in spectroscopy [1], sensing [2] and microscopy [3]. At the same time, multi-wavelength ultrafast lasers have gained significant interest, as well since they are able to simultaneously yield two or more pulse trains at different center wavelengths within the same cavity. These lasers hold the potential to be utilized in many noteworthy applications compared to single wavelength ultrafast pulsed lasers such as in a dual-wavelength or dual-comb spectroscopy [4]. Dual-wavelength spectroscopy is a technique to identify chemical species with fast acquisition rate at a high resolution [5] and requires a mode-locked laser operating in multiple pulse regimes [6]. These multi-wavelength ultrafast lasers could also be used in other applications such as high frequency measurements, fiber communications, fiber testing, and ultrafast optical sensing [7,8]. Recently, the two-micron region has drawn attention for ultrafast laser applications [6,9–11] mainly due to its strong absorption capabilities for OH, CO_2 and NO_2 molecules [12,13]. This gives promise for the use of two-micron dual-wavelength mode-locked fiber lasers for dual-comb spectroscopy, precision metrology, as well as the remote sensing of greenhouse gases [6].

Passive mode-locking has been the preferred approach to produce ultrafast fiber lasers in comparison to the active approach mainly due to its cost-effectiveness and compactness. One of the techniques in passive mode-locking is the nonlinear polarization rotation (NPR) which incorporates polarization controllers and polarization-dependent components into the cavity to induce mode-locking. This technique is able to produce high pulse energies without the risk of pulse breaking [14], but is very sensitive to external perturbations and as such suffers in terms of its stability due to its polarization sensitive components. Another well-known passive mode-locking technique is by using saturable absorbers (SAs). SWCNT-based SAs are preferred for pulse generation due to its fast recovery time and high thermal stability [15]. A noteworthy characteristics of the SWCNT-based pulsed fiber laser is its insensitivity to polarization changes, in addition to being environmentally stable and having broad absorption capable of supporting multiple pulsed-laser signals within the cavity [16,17]. These characteristics of the SWCNT makes them preferred over the NPR technique especially in terms of stability, though at the expense of lower energy outputs.

In this work, a two-micron, mode-locked laser with a dual-wavelength output is proposed and demonstrated. The thulium-doped fiber (TDF) based laser is able to generate a dual-wavelength mode-locked (DWML) output by manipulating the

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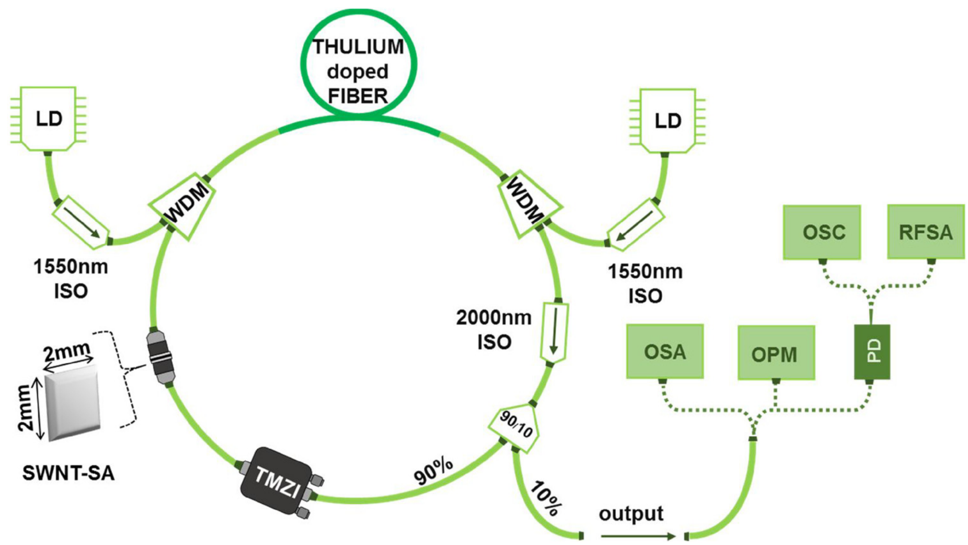

Fig. 1. Schematic of the proposed TDF based DWML fiber laser.

interference peaks of a tunable Mach-Zehnder filter (TMZF) that is integrated into the laser cavity. The use of the TMZF provides a significant advantage to the DWML in terms of high immunity towards external influences, which is a substantial problem in polarization based DWML designs [18–21]. Similarly, TMZF based designs do not require the delicate balancing of intracavity losses [8]. Furthermore, the TMZF is a highly cost effective solution towards generating the desired DWML output as compared to the use of expensive and not easily obtained two-micron fiber Bragg gratings (FBGs) [22], and also allows for a simple setup without the need for multiple optical components [23]. The proposed setup utilizes a bidirectional pumping scheme to obtain a wider amplified spontaneous emission (ASE) output [10], while a SWCNT film SA serves to generate the desired mode-locked output. The proposed DWML fiber laser would have significant uses for high frequency measurement [7] and dual-comb spectroscopy [4] applications.

2. Experimental setup

The experimental setup of the proposed TDF based DWML fiber laser is given in Fig. 1. The cavity is pumped by two Princeton Lightwave 450 1550 nm laser diodes (LDs) in a bidirectional pumping scheme. Both LDs have their outputs connected to the 1550 nm ports of a pair of 1550/2000 nm wavelength-division multiplexers (WDMs) and are capable of generating a combined pump power of 457 mW. Each LD is connected to a 1550 nm optical isolator (ISO) to protect it from back-reflections, which can potentially damage the pump LDs. The common port of both WDMs connected to the ends of a 4 m long TmdF2000 TDF, which serves as the active gain medium in this setup. The TDF has a mode field diameter of 5.0 μm and a peak absorption of ~20 dB/m measured at 1550 nm. The tandem pumping scheme employed in this setup allows the excited Tm^{3+} ions to produce a two-micron output through a $^3H_4 \rightarrow {}^3H_6$ energy transfer. This is a preferred pumping scheme as it can achieve a higher power output as compared to a similar setup employing LDs operating at 790 nm [24]. Furthermore, pumping at 1550 nm allows for a lower rate of reabsorption of the pump signal, allowing for a shorter cavity which is preferable for mode-locked lasers [25].

The 2000 nm port of the WDM configured in the backward pumping configuration is now connected to an ISO optimized for operation at the two micron region. This ensures the unidirectional propagation of the laser signal in the cavity and helps to induce lasing. The ISO is connected to a 90/10 tap coupler, with the 10% port being used to extract a portion of the signal for further characterization and analysis. The 90% port of the coupler is now connected to the afore-mentioned TMZF. The TMZF is characterized using a two-micron wavelength broadband light source and has an insertion loss of 1.2 dB, maximum extinction ratio (ER) of ~31.6 dB, and a full spectral range (FSR) of ~49.9 nm [11].

The output of the TMZF is now coupled to the SA, which is formed by simply sandwiching a 2 mm × 2 mm SWCNT thin film between two fiber ferrules. The SWCNT-based SA, provided by the Centre for Advanced Photonics and Electronics (CAPE), University of Cambridge, United Kingdom, uses a polyvinyl alcohol (PVA) based substrate as the host material and has a modulation depth of 19% and linear absorption of ~8 dB at the two-micron region [11]. The SWCNT was the best choice for producing the DWML, primarily due to its wide and excellent saturable absorption nature from 1 μm to 2 μm [26]. This allows the modelocking of multiple distinct wavelength peaks within the ASE region. The SWCNT is held in place with the help of some index matching gel on one fiber ferrule before the second fiber ferrule is joined to the first with the use of a fiber mating sleeve. Finally, the SA is connected to the 2000 nm port of the WDM in the forward pumping configuration, thus completing the optical circuit.

The 10% extracted signal from the cavity is used to analyze the optical and pulse properties of the generated DWML output. Optical spectrum analysis is performed using a Yokogawa AQ6375 optical spectrum analyzer (OSA) with a resolution of 0.05 nm, while a Thorlabs S302C optical power meter (OPM) with a resolution of 1.0 μW provides optical power measurement. The pulse characteristics are studied using a Yokogawa DLM205 oscilloscope (OSC) and an Anritsu MS2683A radio-frequency spectrum analyzer (RFSA). An 818-BB-51 F Newport InGaAs based photodetector (PD) with a bandwidth of 12.5 GHz serves as an optical-to-electrical bridge between the laser output to the OSC and RFSA. These devices are interchanged at the 10% port as necessary. The setup consists primarily of SMF-28 fibers with the TDF as the gain medium. The total cavity length is measured to be ~22 m, comprising of an 18 m SMF-28 fiber and 4 m TDF. The SMF-28 fiber and TDF has a group velocity dispersion (GVD) of −68.4 $ps^2\,km^{-1}$ and -22.8 $ps^2\,km^{-1}$, respectively at 1958 nm [9]. The net cavity dispersion can be calculated to have a value of – 1.3224 ps^2. A negative net dispersion indicates that the generated mode-locked laser operates in the anomalous dispersion regime.

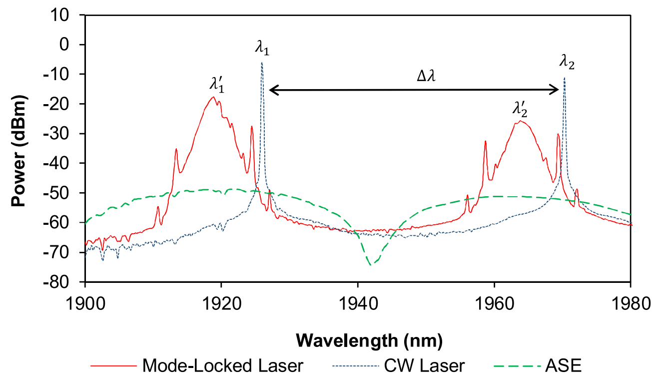

Fig. 2. Lasing output during CW and mode-locked operation, as well as the ASE spectrum.

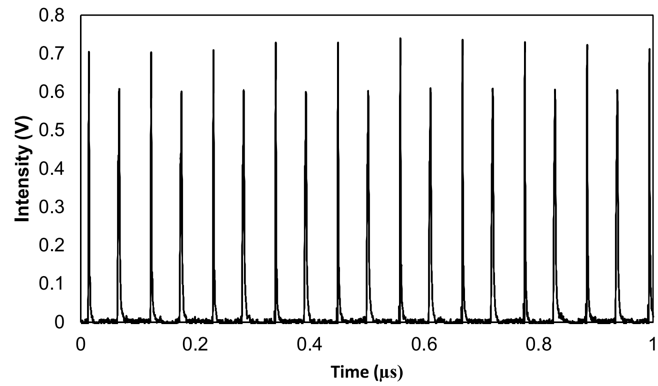

Fig. 3. Oscilloscope trace of the TDF based DWML fiber laser.

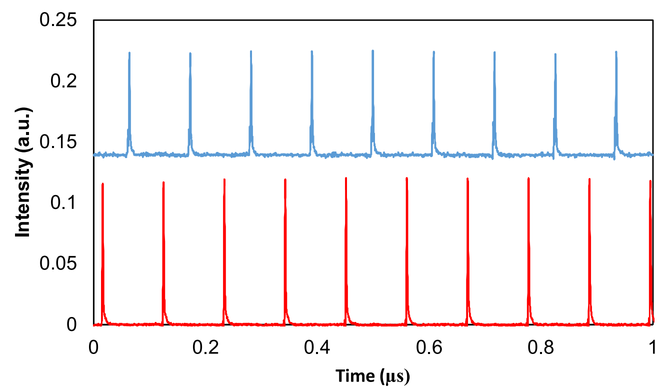

Fig. 4. Separated oscilloscope trace of λ'_1 (red) and λ'_2 (blue) of the TDF based DWML fiber laser.

3. Results and discussions

The TDF based DWML has a continuous wave (CW) lasing threshold of 82.7 mW with the TMZF set to its maximum ER, without the SA incorporated into the cavity. Under CW operation, two distinct wavelengths are observed, designated λ_1 and λ_2 at 1925.8 nm and 1970.2 nm, respectively, giving a total spacing, $\Delta\lambda$ of 44.4 nm between the CW lasing lines. Incorporating the SA into the cavity results in the lasing output becoming mode-locked, starting at 150.4 mW. At this power, two broad optical solitons are observed at both ends of the gain spectrum. The center wavelength of each soliton is designated λ'_1 and λ'_2 with corresponding values of 1919.2 nm and 1963.7 nm. Please take note that λ'_1 and λ'_2 are the shifted generated mode-locked pulses. It is observed that the peak of the two lasing wavelengths experiences a blue-shift from the initial lasing peaks of λ_1 and λ_2 by approximately 6.6 nm. This shift occurs in the direction of a higher gain because of the increase of the overall cavity loss by the inclusion of the material [27] (Fig. 2).

Kelly's sidebands can be clearly observed in both spectra, confirming that the laser is operating in a soliton mode-locking regime. The bandwidth of the mode-locked spectrum of λ'_1 is measured to be 2.1 nm, while the second lasing wavelength is observed to have a slightly broader spectrum at 2.6 nm. The difference in the bandwidth can be attributed to the dispersion in the cavity, where the different wavelengths have dissimilar bandwidth broadening by dispersion. This will directly affect the pulse width, whereby the mode-locked soliton with a broader bandwidth will have a narrower pulse. The pulse width of each spectrum is estimated by computing its time-bandwidth product (TBP) [28,29]. A sech^2 pulse curve fitting is assumed, with the theoretical minimum TBP value being 0.315. The calculated pulse width for the dual-wavelength spectrum is of 1.8 ps and 1.6 ps. Further observation of the spectra reveals that there is the generation of small sub-sidebands at the upper regions of the soliton, which could arise due to the polarization effect, as well as crossphase modulation that can be induced when one or more optical fields are launched into the fiber cavity [30]. The small sub-sidebands can be suppressed by integrating a polarization controller optimized for operation in the two-micron region into the cavity.

The repetition rate of the pulsed laser is given in Fig. 3. Observation of the pulses indicates that rather than a single continuous pulse train, the pulse train observed instead consists of a composite of pulse trains at different group velocities, which was observed by Jiang *et al.* [18]. By utilizing a tunable bandpass filter (TBPF), the pulse train in Fig. 3 can be independently observed as shown in Fig. 4. The repetition rate of both pulse trains is on the average at 9.1 MHz, coinciding with a total cavity length of ~22 m. The pulses are separated in order to accurately measure the pulse width of each spectrum, and, thus confirms the solitonic nature of the mode-locked laser.

The autocorrelator trace is displayed in Fig. 5 whereby λ'_1 and λ'_2 have a pulse width of 2.86 ps and 2.59 ps, respectively. By taking the bandwidth of the mode-locked spectrum, the TBP of each pulse is calculated to be of 0.49 and 0.52 for λ'_1 and λ'_2, respectively. The calculated TBP value is larger than the theoretical value for a sech^2 curve fitting on mode-locked pulses, that is of 0.315. The difference in these values could be related to the use of the tunable bandpass filter that has a narrow output which limits the bandwidth of the mode-locked pulses. A larger TBP value could also be the result of chirping in the pulses, however, the magnitude of chirping could not be determined in the current configuration.

The optical signal-to-noise ratio (OSNR) of the generated DWML output is given in Fig.6 (a) at a resolution of 300 Hz while Fig. 6(b) shows the radio-frequency (RF) spectrum at a larger span to show the harmonics of the laser. The proposed laser has a relatively high OSNR value of 59.1 dB with a fundamental frequency of 9.1 MHz. Minor peaks are also observed at other frequencies, which is again attributed to the different group velocities propagating within the cavity. These peaks however have an ONSR of less than 20.0 dB and can be safely assumed to be independent of the main pulsed output. Since each pulse train has different group velocities, each pulse train should have distinct peaks in its RF signal. The signals can be observed by measuring the RF spectrum at a smaller span at its lowest resolution as shown in Fig. 7. The peak separation is ~3 kHz and this confirms that there are two distinct pulses at a slightly different repetition rate of 9.102 MHz and 9.105 MHz propagating simultaneously in the cavity.

In order to test the optical stability of the mode-locked pulses, the laser is left operational for a total of fifty minutes and the optical spectrum is taken at intervals of every ten minutes as given

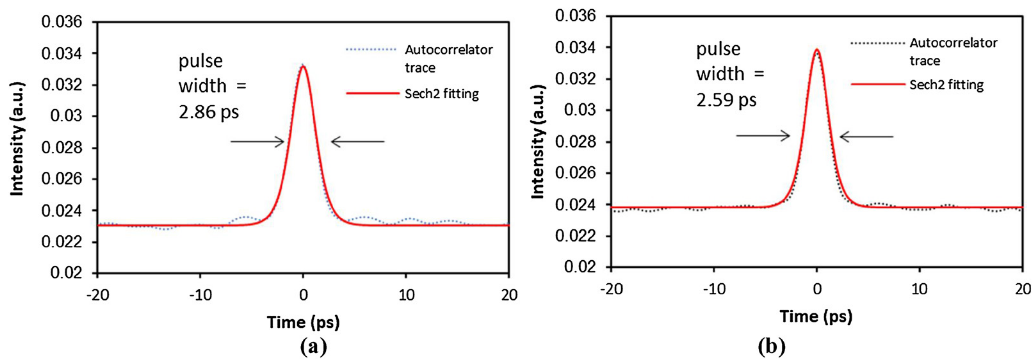

Fig. 5. Pulse width measurement of each soliton pulses (a) λ_1' and (b) λ_2' of the TDF based DWML fiber laser.

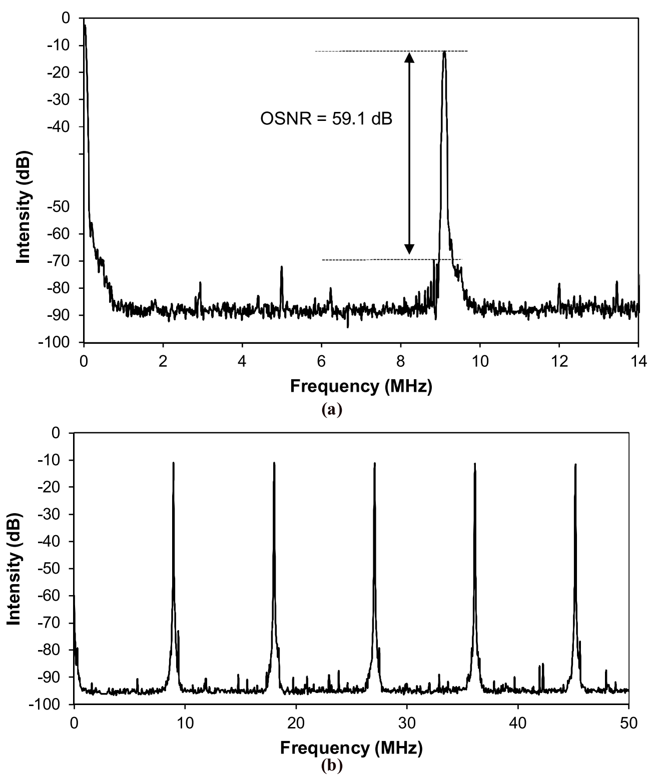

Fig. 6. Frequency-domain spectrum of the pulse train taken at **(a)** its fundamental frequency, and **(b)** its harmonics at a larger span.

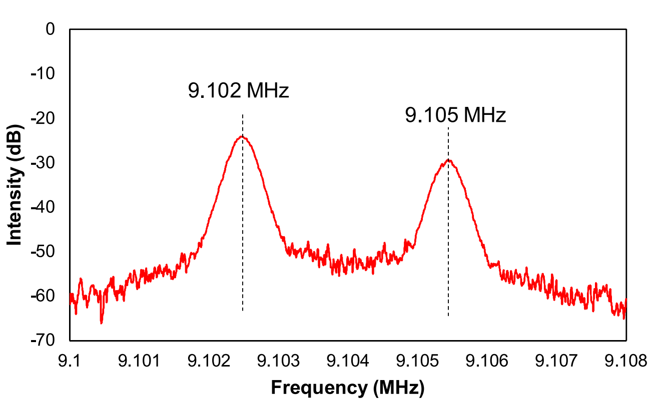

Fig. 7. Two distinct frequency-domain spectrum peaks of the simultaneously running pulse train.

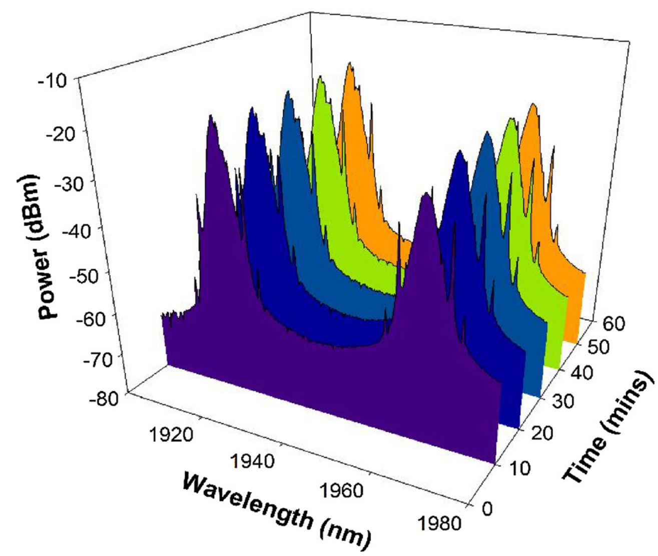

Fig. 8. DWML output over 50 min at 10 min intervals.

in Fig. 8. From the composite spectrum, it can be observed that the wavelength spectrum maintains its shape with respect to time, with lasing wavelength fluctuations of less than 0.1 nm.

The mode-locking threshold of the SA is also of interest, and to study its effects on the proposed laser, the pump power is increased gradually to its maximum power. Starting at the pump power of 166.1 mW, the pulse train of the mode-locked laser destabilizes and begins to show instabilities, indicating that the SA is approaching its mode-locking threshold. Beyond this value, no mode-locking is observed. However, reducing the power stabilizes the output, thus indicating that the SA is still operational and the SA is still undamaged. The DWML output is highly stable and able to provide a high output power with optimal repetition rate and the pulse width, giving it significant potential as a seed source in high-speed gas molecular spectroscopy and sensing. The output of the laser can be further optimized by shortening the cavity or by controlling the cavity birefringence using a polarization controller.

4. Conclusions

A simple and robust scheme for a DWML fiber laser based on a TDF and SWCNT-based SA is proposed and demonstrated. The TDFL uses a TMZF to produce the desired dual-wavelength output while the SWCNT-based SA generates the passive mode-locking pulse output. The cavity employs a 4 m long TDF that is bi-directionally pumped at 1550 nm and can generate a dual-wavelength laser output at 150.4 mW at 1925.8 nm and 1970.2 nm A stable pulse train with a repetition rate of 9.05 MHz and dualwavelength peaks at 1919.2 nm and 1963.7 nm is observed, with calculated minimum pulse width of 1.84 ps and 1.56 ps for each lasing wavelength, respectively. The mode-locked signal has a relatively high OSNR value of 59.1 dB indicating a stable operation and is further verified through continuous measurement over fifty minutes. The proposed laser has numerous applications in ultrafast gas molecular spectroscopy and sensing.

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Author statement

A. S. Sharbirin – Conceptualization, Validation, Investigation, Writing – Original Draft, Visualization.

M. Z. Samion – Investigation, Resources.

M. F. Ismail – Investigation, Writing – Original Draft, Project Administration.

H. Ahmad – Conceptualization, Methodology, Supervision, Project Administration, Funding Acquisition, Writing – Review & Editing.

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