Generation of stable mode-locked fiber laser based MWCNTs in 1.5-µm waveband

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Abstract. Pulses fiber laser had been successfully generated by using multi-wall carbon nanotubes thin film saturable absorber at room temperature. The saturable absorber is incorporated into a ring laser cavity. A stable Kelly sidebands mode-locked pulse spectrum with 1561.3 nm wavelength at the pump power of 86.8 mW. The repetition rate and pulse width of 12.3 MHz and 0.51 picosecond, respectively. A stable operation is observed for an hour at room temperature. These simple and reliable system features offer interesting research study especially in mode-locked pulse generation at 1.5 µm waveband.

1. Introduction

A few years ago, mode-locked fiber lasers (MLFL) had great potential in a multitude of applications such as in material micromachining, terahertz spectroscopy, ophthalmology, space ranging, medical imaging, and optical communication. Substantial efforts have been explored to develop a stable, cost-effective design, high-quality beam, compact and alignment-free laser. MLFL based on erbium-doped fiber (EDF) as an active medium has presented significant advantages and the highest potential for further exploration, especially passive techniques by incorporating a saturable absorber (SA). A passive technique loss modulation is much shorter compared to an active technique. Due to this advantage, many studies have been conducted on EDF-based MLFL by utilizing carbon-based material as SA, for example, carbon nanotubes [1] and graphene [2]. Carbon nanotubes (CNTs) have been chosen as a suitable saturable absorber due to their benefits such as saturation with high-intensity light, very fast recovery time (1-picosecond), efficient light absorber and emitter, broadband operating bandwidth, moderate damage threshold, and low-cost fabrication process.

CNTs typically have two types of carbon wall structure which are single-wall carbon nanotubes (SWCNTs) and multi-wall carbon nanotube (MWCNTs). MWCNTs [3] also have capabilities as higher thermal properties and ease to fabricate, thus attracted great interest and have been focused on by researchers. MWCNTs form a special class of nanotubes due to their morphology and characteristics are similar to SWCNTs however with more resistance to the chemical. The advantageous of MWCNTs over SWCNTs are their mechanical strength which makes it a strong and sturdy material in term of tensile strength and elastic modulus. In addition,
MWCNTs also have the capability to absorb more photons energy per nanotubes [4]. These properties are due to MWCNTs consists of multiple rolled layers of graphene. In the case of MWCNTs, the only outer layer is modified while protecting the inner layer from oxidation or damage, thus having a higher damage threshold compared to SWCNTs. Therefore, MWCNTs have been proposed to be utilized in cavity rings in order to achieve pulse fiber laser.

Recently, the emergence of other 2D materials have been explored and have successfully generated pulse fiber laser, for example, Bismuth selenide [5, 6], Bismuth telluride [7, 8], Molybdenum disulfide [9], Molybdenum diselenide [10], black phosphorus [11, 12], titanium dioxide [13] and zinc oxide [14]. All these materials have remarkable properties, which makes them a suitable material as a SA. Although with the dumping of new materials, MWCNTs still can be idealized as a suitable saturable absorber and still relevant to generate mode-locked and Q-switched pulse.

In this paper, a compact EDF-based MLFL is successfully achieved by using MWCNT as a SA. The MWCNTs SA is used into the ring cavity to achieve a stable MLFL in the region of a 1.5 µm waveband. The broad bandwidth of the laser spectrum is centered at 1561.3 nm with short pulse duration and repetition rate of 0.51 picosecond and 12.3 MHz, respectively.

2. Methodology
The experimental setup for multi-wall carbon nanotubes based MLFL is depicted in Figure 1, which comprise 60cm of EDF as the gain medium, a single-mode fiber (SMF) with a length of 500 m, and a multi-wall carbon nanotube saturable absorber sandwiched between two fiber ferrules in a ring cavity fiber laser. The EDF is pumped by a 974nm laser diode which had to be attached to a 980/1550 nm wavelength division multiplexer (WDM). An insensitive polarization isolator is connected to ensure the propagation of the laser in unidirectional, and for this work, in a clockwise direction. A polarization controller (PC) is used in the cavity to optimize the birefringence. The other end of the PC is linked to a MWCNT/PVA-based SA and then connected to a 95:5 optical coupler (OC1), where 5% of OC1 port is extracted to another optical coupler (OC2) and then connected to measurement equipment. An oscilloscope, a radio frequency spectrum analyzer (RFSA), an optical spectrum analyzer (OSA) with 0.02 nm spectral resolution and an autocorrelator are used for characterizing the generated pulse fiber laser from the cavity. The 95% of the OC1 port is attached to a SMF and then back to another end of WDM in order to complete the ring cavity configuration.

![Figure 1. The proposed MWCNTs based mode-locked fiber laser generation in 1.5 µm waveband](image-url)

The SA is formed by MWCNTs polymer composite thin film with polyvinyl alcohol (PVA). The fabrication process is reported in [15]. The SA has a length of 1–3µm, thickness of about 50µm and diameter range from 10 µm to 20 µm.
3. Results and Discussion
The lasing threshold for EDFL is at 48.5 mW with central wavelength and peak power of 1560.50nm and -33.9 dBm, respectively. The lasing wavelength remains stable by increasing the pump power up to 74.8mW. As the pump power is increased to 86.8mW, the soliton mode-locking has self-started to generate in the ring cavity. The broad mode-locked spectrum is centered at 1561.3 nm with a power level of -32.74 dBm. The optical spectrum is depicted in Figure 2 with the Kelly sidebands spectrum indicated the total cavity dispersion of the pulse in an anomalous dispersion with a total cavity length of approximately 504 m. The broadening of the MLFL spectrum is because of the dispersion of 500 m SMF. The oscillation pulse train of MLFL is shown in Figure 3. Mode-locked pulse with 80.90 ns time interval between pulses can be translated to 12.3 MHz repetition rate, which corresponding to 504 m cavity length. As we decreased or increased the pump power, nothing changes in the repetition rate of the mode-locked pulse. This behaviour proved that the generated pulse train is corresponding to the mode-locking process and is not Q-switched. This is due to the repetition rate of Q-switched changes with the changes of pump power. The generated mode-locked pulse is also measured in repetition rate by radio frequency spectrum analyzer (RFSA) and pulse width by autocorrelator.

Figure 2. The generation of soliton mode-locking with anomalous dispersion at 1561.3 nm wavelength

Figure 3. Oscillation of MLFL at 12.3 MHz
Figure 4. Frequency domain of MLFL at 12.3 MHz

Figure 5. An ultrashort pulse width of MLFL at 0.51 ps

Figure 4 shows the result of the radio frequency spectrum for MWCNTs based mode-locked EDFL with a fundamental harmonic frequency of 12.3 MHz. The signal-to-noise ratio (SNR) is about 58 dB which show the stable operation of the MLFL has been generated in the ring cavity. In addition, no spectral modulation observed in RFSA thus also proved the stability of generated mode-locked pulse. In fact, the MLFL operating signal can last for several days without interference or losing the mode-locking pulse. The stability is also attributed to its remarkable thermal conductivity, where our MWCNTs based SA have capabilities as higher damage threshold. The pulse width of MLFL is about 0.51 picosecond measured by using an autocorrelator. This indicates that the generated pulse occurs at a very fast rate and, to be exact, its ultrashort pulse.

4. Conclusion
A stable and compact mode-locked EDFL is successfully achieved by sandwiching MWCNTs SA between the fiber ferrules in ring cavity configuration for 1.5µm spectral regions. The proposed mode-locked with a MWCNTs acts as a SA is capable of generating a stable mode-locked pulse with a broadband spectrum centered at 1561.3 nm and is observed in a stable condition for over an hour at room temperature. The pulse train repetition rate and pulse widths were 12.3 MHz and 0.51 picoseconds, respectively. In addition, this configuration is relatively simple, and compact demonstrate a promising passive technique to generate mode-locked pulse fiber laser.
5. References

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