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<td><strong>Citation</strong></td>
<td>Liu, H. H., Yang, Y., &amp; Chow, K. K. (2013). Enhancement of thermal damage threshold of carbon-nanotube-based saturable absorber by evanescent-field interaction on fiber end. Optics express, 21(16), 18975-18982.</td>
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<td><strong>Date</strong></td>
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<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/18442">http://hdl.handle.net/10220/18442</a></td>
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Enhancement of thermal damage threshold of carbon-nanotube-based saturable absorber by evanescent-field interaction on fiber end

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Abstract: We present a scheme of fiber-connector-type carbon-nanotube-based saturable absorber (CNT-SA) with enhanced thermal damage threshold, in which the CNTs are deposited on the fiber connector end in a ring pattern for evanescent-field interaction instead of direct interaction. The thermal damage threshold of such CNT-SA is found to be increased by around 130% compared with an evenly deposited one. An all-fiber Fabry-Perot (FP) linear cavity passively mode-locked laser is further constructed incorporating the prepared CNT-SA, where the optical power is confined in a relatively short laser cavity to investigate the thermal damage threshold and the performance of the CNT-SA. Stable output pulses with a fundamental repetition rate of 211.84 MHz and a pulse width of 680 fs are generated from the fiber laser. The mode-locking operation can be maintained an intra-cavity average power of 30 mW, indicating that the CNT-SA can withstand a relatively high optical power without performance degradation.

OCIS codes: (160.4330) Nonlinear optical materials; (060.3510) Lasers, fiber.

References and links
1. Introduction

Passively mode-locked fiber lasers using carbon-nanotube-based saturable absorbers (CNT-SAs) have attracted much research interest due to their potential applications for ultra-short pulse generation with simple cavity structures [1–5]. The conventional method to construct a CNT-SA can be simply deposited CNT layers or CNT-polymer films sandwiched between fiber ferrule connectors or fiber ends [6–9]. In such schemes, the central part of the optical field which carries the majority of power can effectively interact with the deposited CNTs. However, one concern of these schemes is the relatively low thermal damage threshold. Previous report shows that an optical power higher than 30 mW could damage CNTs by the generated heat [10]. One alternative solution to tackle this problem is to utilize the interaction of CNTs with evanescent-field of the propagating light along the optical fiber [11–14]. In order to have a CNT-light interaction, pre-processing of the fibers is required including side-polishing [11, 12], tapering [13], and chemical etching [14]. As the CNTs only interact with a portion of light, the thermal damage threshold of such CNT-SAs can be greatly increased. However, such schemes involving the modification of the fiber structure can generate extra polarization sensitivity and scattering loss. Also, the quality of such pre-processing of the optical fibers largely affects the performance of the CNT-SAs. In order to overcome these limitations and improve the thermal damage threshold, fiber-connector-type CNT-SAs with various packaging have been reported for efficient heat-dissipation or heat-resistance including nanoporous-alumina-membrane-embedding [15], SiO₂-hosting [16], and siloxane-sealing [17]. As a result, the thermal damage threshold of CNT-SAs can be raised to 120 mW [16]. Recently, a fiber-connector-type CNT-SA sealed in nitrogen environment has been demonstrated [18]. Since the oxidation is prevented by the surrounded nitrogen gas, such CNT-SA can operate at a high power level without deterioration. However, these methods incorporate extra materials as well as gas sealing which lose the basic simplicity advantage of CNT-SAs.
In this paper, we propose and demonstrate a scheme of fiber-connector-type CNT-SA with enhanced thermal damage threshold. By controlling the deposition process, the CNTs are optically deposited on the fiber connector end in a ring pattern to establish an efficient evanescent-field interaction between the propagating light and the deposited CNTs. Such scheme has notable advantages including high thermal damage threshold, compact device with low loss, polarization-insensitive, and easy fabrication. The thermal damage threshold of the CNT-SA with ring pattern is found to be improved by ~130% compared with the one with the deposited CNTs evenly covering the fiber core region. An all-fiber Fabry-Perot (FP) linear cavity mode-locked laser is further constructed incorporating the prepared CNT-SA, where the optical power is confined in a relatively short laser cavity to investigate the thermal damage threshold and the performance of the CNT-SA. Output pulse train with a fundamental repetition rate of 211.84 MHz and a pulse width of 680 fs is obtained. The developed short-cavity mode-locked fiber laser shows a stable operation at a maximum pump power of 240 mW with a corresponding intra-cavity average power higher than 30 mW, suggesting that the CNT-SA can withstand a relatively high optical power without performance degradation.

2. CNT-SA preparation and optical characterization

The operation principle of the proposed CNT-SA is based on the interaction between the evanescent-field of the propagation light and the deposited CNTs in a ring pattern on fiber connector end as illustrated in Fig. 1. Figure 2(a) depicts the field distribution of the fundamental mode in a standard single-mode fiber (SMF). It is calculated that around 50% of the optical power is distributed beyond the diameter of 6.5 μm while less than 1% of optical power is distributed exceeding a diameter of 22 μm. In order to achieve an efficient evanescent-field interaction as well as minimize the optical absorption-induced heating, the inner ring diameter of CNTs on the fiber connector end is optimized between 9 and 15 μm.

The fabrication of the CNT-SAs utilizes the optically-driven deposition method. The movement of CNTs suspended in solution towards the connector end could be explained by thermophoresis, in which the temperature gradient is caused by heating due to optical absorption [6]. The formation of CNTs in a ring pattern on the end-facet of the connector is believed to be a result of balancing between the scattering force and the gradient force.

Fig. 1. Schematic illustration of the proposed carbon-nanotube-based saturable absorber (CNT-SA) that CNTs are formed onto the end-facet of the fiber in a ring pattern.
Fig. 2. (a) Calculation of the field distribution of the fundamental mode in a standard single mode fiber, (b) microscopic image of the connector end deposited with CNTs in a ring pattern.

generated by the optical radiation [6, 7]. Such gradient force attracts CNT particles in the direction of increasing intensity while the scattering force pushes CNT particles in the direction of propagation. Because of the divergence of the optical radiation in a standard SMF [19], the gradient force is insufficient to overcome the scattering force. As the radiation field distribution is circularly symmetric, a ring pattern of CNTs can be formed around the core region. The CNTs in this experiment are made by a bulk production method called high-pressure CO conversion (HiPCO). By controlling the HiPCO process and the resultant the nanotube diameters, the optical absorption property of CNTs can be controlled. The synthesized CNT powder is dispersed in dimethylformamide (DMF) solvent, and only the homogeneous part is taken after centrifugal separation. The transmission spectrum of the prepared CNTs shows a desirable absorption peak near the C-band [20]. A seeded light from a continuous-wave (CW) 1.55-µm laser diode (LD) is amplified by an erbium-doped fiber amplifier (EDFA). A fixed connection/physical contact (FC/PC) connector guides the light into the CNT solution. Since the optical manipulation of CNTs is generally dependent on the incident power and period [21], an in situ monitoring process for the CNT deposition is performed. An optical circulator is inserted before the connector for collecting the reflected power and protecting the light source. When the EDFA is turned on with an output power of 20 dBm for 10 seconds, a dramatic increase of 21 dB in reflectivity is observed. The increase indicates that the connector end is changed from being surrounded by the DMF solution only to being coated with CNTs [22]. We immerse the connector end in the CNT solution for 2 minutes until the increase in reflectivity is observed before taken it out from the solution. In order to dry up the residual DMF solution, the EDFA is kept on for another minute when the connector end is held in the air. Figure 2(b) shows the microscopic image of the end-facet of the connector after the CNT deposition. A ring pattern is observed with the inner diameter of ~10 µm and the outer diameter of ~25 µm.

Since the optical field decreases with the center of the fiber core dramatically as shown in Fig. 2(a), the inner ring diameter of CNTs dominates the optical absorption while the DMF residuals with larger than the ring diameter doesn’t have significant effect on the performance of the device. In general, a higher optical power is required to form a larger inner diameter through a stronger scattering force, while the duration of deposition controls the outer ring diameter and the resultant layer thickness. Practically, the CNT layers in ring pattern can be reproduced with similar setup and CNT solution. In our experiment, we have initially obtained deposited CNT layers in ring pattern with an inner ring diameter of 14 and 38 µm at a power level of 20.7 and 22 dBm, respectively. As the optical field is mainly confined in the core region of the fiber, it is expected that the CNT-SA with a larger inner ring diameter can have higher thermal damage threshold which exhibits lower optical absorption compared to one with a smaller inner ring diameter. The CNT-SA with the inner ring diameter of around
14 µm is measured to be able to withstand an intra-cavity average power of 126 mW. In order to obtain a desirable saturable absorption as well as a high thermal damaged threshold for mode-locked laser applications, the CNT-deposited connector end with an inner ring diameter around 10 µm is adopted in our experiment. The prepared CNT-deposited connector end is mated to a clean FC/PC connector to create a CNT-SA. The total insertion loss of the CNT-SA is about 1 dB and the polarization dependent loss (PDL) is measured to be 0.05 dB at 1.55 µm. As evanescent-field interaction only occurs through a CNT thin film, the accumulation of polarization-dependent absorption by the CNTs in the proposed device is smaller in contrary to the one with evanescent-field interaction over a longer interaction length [11, 14].

The nonlinear transmission property of the prepared CNT-SA is characterized by a 1.55-µm mode-locked fiber laser. The laser delivers a pulse train with a pulse width of 260 fs, a repetition rate of 68.27 MHz, and an average power of 20 mW. Before the pulse train is launched into the CNT-SA, a tunable attenuator is adopted to adjust the input average power. Figure 3(a) shows that the optical absorption of the CNT-SA exhibits saturation when the input power is increased. The saturable absorption and non-saturable loss are estimated to be 2.6% and 16.3%, respectively. The saturable absorption in the different polarization state of the incident light is believed to be minimal due to the small PDL of the device. Since the effective mode area of the standard SMF is around 100 µm², the saturation fluence of the CNT-SA, defined as the saturation energy per unit area, is estimated to be 47.2 µJ/cm². As a comparison, we prepare a CNT-SA that CNTs are directly sprayed onto the connector end and evenly covering the entire core region. It bears a similar insertion loss with the proposed CNT-SA while exhibits a lower saturation fluence of ~22.4 µJ/cm². The relatively high saturation fluence in the CNT-SA with a ring pattern is a result of the efficient evanescent-field interaction as only a portion of light interacts with the CNTs.

In order to study the long-term reliability of the CNT-SAs which are exposed to high incident power, we characterize the real-time power-dependent transmission of the CNT-SAs for hours. Although the roles of the peak power and the average power in the damage thresholds of CNT-SAs are yet confirmed, it has been reported that for pulsed and CW laser operation the damage of CNT-SAs takes place at similar power levels [18]. We use a CW 1.55-µm LD as the light source followed by a variable-gain EDFA. The CNT-SAs with and without ring pattern are characterized for comparison. Figure 3(b) shows the normalized-transmission of the CNT-SA with CNTs evenly covering the core region at different incident power levels. From the results, it is clearly observed that the transmission starts decreasing after the laser is on with an incident power of 30 mW. Such decrease rate of the transmission can be used to describe the performance of CNT-SAs over time. It is estimated to be 14% per hour for the CNT-SA without ring pattern from the results. Since the high incident power induces graphitization and structure variation of CNTs, the absorption of CNTs increases [10].
Fig. 3. (a) Measurement of the nonlinear transmission of the CNT-SA with CNTs in a ring pattern, (b) the real-time normalized-transmission (n-T) of the CNT-SA with CNTs in a ring pattern (upper) and the one with CNTs covering the entire core region (lower) when they are exposed to different incident powers.

On the other hand, the CNT-SA with a ring pattern exhibits much less increase in absorption with an input power of ~70 mW for more than 5 hours. The decrease rate of the transmission is estimated to be less than 0.04% per hour. The results suggest that the thermal damage threshold of such a CNT-SA is increased by around 130% compared with the evenly deposited one.

3. All-fiber FP cavity mode-locked laser setup and experimental results

A 1.55-µm FP linear-cavity passively mode-locked fiber laser is further constructed to investigate the performance of the fabricated CNT-SA as shown in Fig. 4. In general, the fundamental repetition rate of the laser is determined by:

\[ f_{\text{rep}} = \frac{c}{2nL} \]  

(1)

where \( c \) is the velocity of light in vacuum, \( L \) is the cavity length, and \( n \) is the refractive index of the fiber core. Compared with the ring-configuration mode-locked fiber lasers, a linear-configuration FP mode-locked laser can achieve a shorter cavity length thus a higher repetition rate [23, 24]. It is reported that such short cavity laser tends to encounter an issue that the laser is significantly heated up during operation [24]. The mode-locking operation could be failed by any of the cavity components which cannot endure the generated heat. Therefore, the thermal damage threshold of SA becomes crucial. In the experiment, the prepared CNT-deposited connector end is mated to a highly reflective mirror (mirror-2) to serve as a reflective SA. In order to shorten the cavity length and reduce the intra-cavity loss, the pump source consisting of a 976-nm LD and a 980/1550-nm wavelength-division multiplexing (WDM) coupler is located outside the master oscillator. A dielectric mirror (mirror-1) is included to couple the pump into the laser cavity and extract 10% of the power at the emission wavelength from the laser cavity. A 0.16-m-long erbium-doped fiber (LIEKKI Er80) with a group velocity dispersion (GVD) parameter \( \beta_2 \) of \(-0.022 \text{ ps}^2/\text{m}\) is used as the gain medium. A fiber-based polarization controller (PC) is incorporated to match the roundtrip state of polarization. An isolator located at the output port blocks the deleterious reflection from the end-facet of the port. The total length of the fiber inside the master oscillator is ~0.49 m and the net \( \beta_2 \) is managed to be \(-0.022 \text{ ps}^2\) for soliton shaping.
Fig. 4. Experimental setup of an all-fiber Fabry–Perot cavity mode-locked laser incorporated with the prepared CNT-deposited connector end: wavelength division multiplexing (WDM); erbium-doped fiber (EDF); polarization controller (PC); highly reflective dielectric mirror (−1, −2).

Fig. 5. (a) Output power against pump power and the arrows indicate the power threshold for each state: continuous-wave (CW); Q-switching (QS); and Q-switched mode-locking (QSML), (b) output optical spectrum (the inset shows oscilloscope trace of the output), (c) autocorrelation trace; and (d) RF spectrum (inset shows wideband RF spectrum up to 3 GHz).

In the experiment, the laser transits from the state of Q-switching to mode-locking when the pump power approaches a maximum value of 240 mW as shown in Fig. 5(a). The pump power threshold for single-soliton generation is found to be 96 mW. To achieve single soliton with a relatively high output power, the pump power is fixed at 150 mW. Figure 5(b) shows the corresponding optical output spectrum. The center wavelength is 1563.3 nm and the 3-dB bandwidth is estimated to be 4.4 nm. The output pulse train is given in the inset of Fig. 5(b), exhibiting little change on the envelope. The autocorrelation trace of the output pulse is measured to be around 680 fs with a sech$^2$-pulse shape fitting as shown in Fig. 5(c). The calculated time-bandwidth product is 0.368, indicating that the optical pulse is nearly transform-limited. Figure 5(d) shows the RF spectrum of the pulse train with a fundamental repetition rate of 211.84 MHz corresponding to the cavity length. The RF spectrum with a frequency span of 500 kHz and a resolution of 200 Hz shows an extinction ratio of 83 dB at the fundamental frequency, indicating that a stable mode-locking is obtained. The inset of
Fig. 5(d) further depicts the wideband RF spectrum up to 3 GHz. There is no sideband among the harmonic frequencies which further confirms the stable mode-locking operation.

When the pump power exceeds 160 mW, multiple pulses are generated within one round-trip due to the soliton energy quantization [25]. When the pump power is pushed up to 240 mW, the intra-cavity average power of the constructed FP mode-locked laser is higher than 30 mW. The long-term stability of the developed FP mode-locked fiber laser with an intra-cavity power higher than 30 mW is further investigated for a 12-hour continuous operation. The output of the FP mode-locked fiber laser shows no observable change in both optical spectrum and RF spectrum. It demonstrates that the proposed CNT-SA can withstand a relatively high optical power without significant performance degradation. Previous report shows that the FP mode-locked fiber laser with high repetition rate is built with a CNT-film attached to the end-facet of a special gain fiber with a core diameter of 14 µm [26]. Owing to the relatively large mode field diameter of the fiber, the CNT-SA can sustain a relatively high intra-cavity power. It is worth noting that the CNTs are deposited on the end-facet of a ferrule connector with standard SMF in our work. Benefiting from the evanescent-field interaction of the proposed CNT-SA, the developed FP mode-locked fiber laser can have stable operate at a relatively high power level.

4. Conclusion

Targeting for robust and compact carbon nanotube based saturable absorbers with enhanced thermal damage threshold, we have demonstrated a scheme with CNTs optically deposited on fiber connector ends in a ring pattern for evanescent-field interaction instead of direct interaction. The thermal damage threshold of the CNT-SA with a ring pattern is found to be improved by ~130% compared with the one with CNTs covering the entire core region. The CNT-SA is then incorporated into an all-fiber FP cavity for mode-locking. A pulse train with a fundamental repetition rate of 211.84 MHz and a pulse width of 680 fs is achieved. The results suggest that such a CNT-SA can withstand a relatively high optical power without degradation.

Acknowledgments

The authors would like to acknowledge Dr. K. Wu for providing the fiber mirrors. This work was partially supported by Academic Research Fund Tier 1 Grant (RG22/10) of Nanyang Technological University, Singapore.