# Passive mode-locked lasing by injecting a carbon nanotube-solution in the core of an optical fiber

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**Abstract:** In this paper, we propose a saturable absorber (SA) device consisting on an in-fiber micro-slot inscribed by femtosecond laser micro fabrication, filled by a dispersion of Carbon Nanotubes (CNT). Due to the flexibility of the fabrication method, efficient and simple integration of the mode-locking device directly into the optical fiber is achieved. Furthermore, the fabrication process offers a high level of control over the dimensions and location of the micro-slots. We apply this fabrication flexibility to extend the interaction length between the CNT and the propagating optical field along the optical fiber, hence enhancing the nonlinearity of the device. Furthermore, the method allows the fabrication of devices that operate by either a direct field interaction (when the central peak of the propagating optical mode passes through the nonlinear media) or an evanescent field interaction (only a fraction of the optical mode interacts with the CNT). In this paper, several devices with different interaction lengths and interaction regimes are investigated. Self-starting passively modelocked laser operation with an enhanced nonlinear interaction is observed using CNT-based SAs in both interaction regimes. This method constitutes a simple and suitable approach to integrate the CNT into the optical system as well as enhancing the optical nonlinearity of CNT-based photonic devices.



**OCIS codes:** (140.4050) Mode-locked lasers; (190.4400) Nonlinear Optics, Materials

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## 1. Introduction

Ultrafast fiber laser technology is rapidly gaining ground over conventional solid state lasers for many commercial applications due to their high beam quality, reliability, efficient heat dissipation and compact size. Hence, fiber lasers are routinely used in areas such as optical communications, microscopy, spectroscopy and material processing [1]. The preferred method to achieve pulse operation in a fiber laser is to introduce into the optical system an intensity-dependent component that discriminate in favor of pulse formation over continuous wave lasing. This pulse-inducing mechanism, known as passive mode-locking is generally preferred due to its simplicity and the ability to produce transform-limited pulses without the need for any external active devices such as modulators. In practice, this is generally achieved by using a saturable absorber (SA) which absorbs the incoming light linearly until it reaches a certain threshold intensity, after which it saturates and becomes transparent [2].

Carbon Nanotubes, a material from the fullerene family, exhibit interesting electronic and optical properties and have found several applications in photonics which include nanometre-scale devices for light generation, photo-detection and photovoltaic devices [3, 4]. Of particular interest for this paper is the optical absorption properties of CNT which is of saturable, intensity-dependent nature and hence it is an exceptional material to employ for passively mode-locked laser operation [5]. There is now extensive literature pointing to the advantages of using CNT-SA over other devices such as semiconductor-based saturable absorbers mirrors (SESAM) and Nonlinear Optical Loop Mirrors (NOLM) for the passive modelocking of fiber laser. Such advantages include broadband operation, compatibility with fiber, simplicity of fabrication, fast recovery time and device flexibility [5]. In addition, CNTs exhibit a very high third order nonlinearity which has great potential towards the implementation of optical switches [6]. Since the first demonstrations of CNT-based SA [5], the device design has evolved towards more robust, compact and reliable configurations, initially spray-coating was used to directly apply a CNT film into a fiber ferrule or other substrate. Sprayed films however, are subject to mechanical damage due to their direct physical contact with ferrules and optical power induced thermal damage. Several methods to embed the CNTs into a host material, generally polymers, have been proposed. This approach has several advantages such as, allowing a fine control over the CNT concentration and facilitating the distribution of CNT homogeneously in the host material which suppresses the detrimental effects agglomeration and bundling [7]. By embedding the CNTs into a polymer, there are also protected from the mechanical damage and degradation suffered when free standing on air. Therefore, most of the current research employs devices based on a variation

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of polymer embedded CNTs [8–14]. Our current research is focusing on implementing SAs and nonlinear devices with good quality CNT dispersion, low losses, resistance to thermal damage and increased nonlinearity and interaction lengths for the realization of high power fiber lasers.

Additionally, increasing the interaction length between the CNTs and the optical field can be used for the fabrication of nonlinear optical switches since the optical nonlinearity of a CNT device is directly proportional to the optical power (P) and to the interaction length between the optical field and the nonlinear material (L). Considering these factors, the simplest approach to enhance the nonlinearity of the device is to increase the interaction length between the nonlinear optical media (CNT) and the optical field. Several reports have demonstrated enhanced nonlinear interactions by applying the CNTs to a D-shape [15–17] or tapered fibers [11, 18] and more recently by filling a hollow optical fiber with a dispersion of CNT [12]. The above approaches all exploit the evanescent field interaction between the optical field and the CNTs hence only the tail of the evanescent field (a small fraction of the optical power) directly interacts with the CNT, thus increasing the damaged threshold and allowing high power lasing. This means that the central part of the waveform, which carries the majority of the optical power is not in direct contact with the CNTs. Consequently, we are still interested in developing a method by which the CNT interact directly with the center of the propagating waveform, and thus with the peak power of the pulse.

An attractive line of research to achieve long direct interaction in CNT based devices consists on embedding the CNTs in a host material and fabricating CNT-doped Polymer optical waveguides and fibers [13, 14]. However, the fabrication of efficient devices using those methods is proving difficult and thus far; high insertion losses and mode mismatching means that stable mode-locked lasing operation is difficult to accomplish.

We recently proposed a method to incorporate the CNT into the optical system by using a micro-fluidic channel inscribed across a standard single-mode (SMF) optical fiber by femtosecond laser inscription [19]. Integration, compactness, stability and low insertion losses are ensured by directly fabricating the SA within the optical fiber. In that report, we demonstrated stable passively mode-locked operation with a 2μm diameter channel crossing the core of the SMF fiber. In this paper, we demonstrate how such method can be modified to expand the interaction length between the optical field and the CNTs, consequently increase the nonlinearity of the device. By increasing the interaction length we expect to achieve a deeper modulation of the SA, leading to shorter pulses, such effect is observed experimentally in this paper. Additionally, we apply the flexibility of the microchannel fabrication technique, to fabricate devices that employ both a direct field interaction and evanescent field interaction. It is worth noting that this approach does not require special fibers or splices since in all cases the SA devices are directly integrated into a standard SMF fiber.

## 2. Fabrication of the CNT-SA

The fabrication process of the micro-slots has been described in detail elsewhere [20]. A linear structure is inscribed across a standard single-mode fiber (SMF) by using a tightly focused infrared femtosecond laser beam. The length of the device along the fiber is extended by inscribing adjacent structures, hence inscribing a rectangle-shaped region of optically modified material. The second step consists on the etching of the fiber in a 5% hydrofluoric acid (HF) in an ultrasonic bath for selective removal of the laser modified regions which is etched at a rate of 100:1 with respect to the unmodified region. Using this technique, we can easily control the dimensions, and location of the microfluidic device within the optical fiber. The structure of the fabricated micro-slots is depicted in Fig. 1. Several devices were fabricated where the micro-slot cross the fiber through the center of the core. Those devices had a thickness (t, in Fig. 1) between 1μm and 2μm. In this paper, we will compare the performance of 3 devices with lengths (l) along the fiber of 2μm, 50μm and 200μm. The fabrication method, offers a great flexibility to fabricate complex structures at any desired location within the fiber. We made use of that flexibility to also investigate the evanescent field interaction by fabricating a micro-slot separated from the core a distance of 1μm and

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with a thickness of 2μm and a length of 200μm. The structure of the micro-slot device exploiting the evanescent field interaction is depicted in Fig. 1(b).

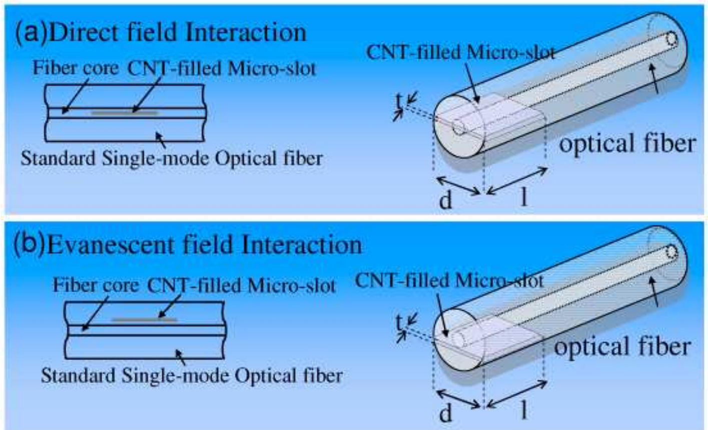


Fig. 1. Diagram of the microslot fabricated for this work. (a) Microslot cross through the core of the fiber, hence the CNT directly interact with the center of the waveform. (b) By fabricating the microslots a given distance away from the core, we can work with an evanescent interaction between the CNT and the optical field.

All the microfluidic devices were then filled with a solution of Commercial CNTs fabricated by the High-Pressure CO Conversion (HiPCO) method, which had been previously dispersed in Dimethylformamide (DMF) solvent. DMF allows the efficient dispersion of the CNT and it is transparent to light at wavelengths relevant to optical communications. In addition, its refractive index is 1.43, close to that of the core of the optical fiber; hence it contributes to preserving the wave-guiding conditions of the fiber. The process of dispersing the CNT in the solvent is of key importance to ensure that bundling caused by Van der Waals interactions is minimized. Bundling not only increases the transmission losses due to scattering but it has also a suppressing effect on the saturable absorption and third order nonlinearity of the device [7]. The concentration of CNT in the solution was approximately 70 parts per million (ppm) and only the visually homogeneous part of the CNT solution was used for the experiment. By working with a low concentration of CNT we can ensure minimal agglomeration.

## 3. Experimental results

The CNT-filled microfluidic devices were inserted into a fiber laser ring cavity consisting of an erbium-doped fiber amplifier (EDFA) as the gain medium. 10% of the intracavity light is coupled out while the remaining 90% of the intracavity optical power is launched back into the cavity to provide the laser feedback. Cavity dispersion was optimized by adding several meters of standard single-mode fiber (SMF). Intracavity polarization was managed by a polarization controller (PC) and an optical isolator is used to ensure unidirectional operation. The passively mode-locked fiber laser configuration is depicted in Fig. 2 (a).

We inserted the CNT-filled microslots into the ring cavity and studied their performance as SAs. As expected, the three microslots of similar thicknesses and lengths of 2μm, 50μm and 200μm presented increasing insertion losses of 0.5dB, 1.2dB and 8.9dB respectively. The origin of the losses for the SA device can be classified as follows; coupling and guiding losses rising from the refractive index mismatching between the injected solution and the core of the fiber [21] and the linear and nonlinear losses that rise from the interaction with the CNT. Without the CNT, taking into account that the refractive index of DMF (1.43), and the dimensions of the microslots, we can estimate that the coupling and transmission losses [21,22]. We estimate that the insertion losses are less than 0.2dB and 0.5dB from the microchannels with lengths of 2μm and 50μm, and we expect a linear increase of the losses

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with increasing dimensions of the microslot. The remaining insertion losses are caused by linear and nonlinear interaction with the CNT, the absorption properties of the CNT on DMF solution are described elsewhere [19]. All of these microslots were inscribed across the core, hence there is a direct interaction between the optical field and the CNT. Self-starting passively mode-locked laser operation was observed with all three devices. Operation with intracavity powers as high as 23dBm, without performance degradation was observed. This compares favorably with sprayed samples that suffer permanent thermal damage at intra-cavity optical power in the order of 15dBm [17]. We believe that the improved robustness is a result of the efficient heat dissipation of the liquid solution. In Fig. 2 (b), the optical spectra of the ring cavity laser output are shown when employing each of the three SAs, soliton-like optical spectra with the presence of the Kelly side-bands characteristic of soliton operation in fiber lasers. The ring cavity employed was unchanged throughout the experiment with each of the SA. The power measured from the EDFA was 23dBm. Under those conditions the spectral bandwidth and pulse duration were measured, with output powers of 13.5dBm for the 2µm long SA, 11.2dBm for the 50µm-SA and 7dBm for the 200µm SA. We observed spectral broadening of the laser output with increasing interaction lengths with spectral bandwidths of 1.1nm, 1.6nm and 2.8nm respectively for the increasing lengths. Figure 2 (c) shows the autocorrelator trace measurements, assuming a $sech^2$ pulse shape for the three samples, yielding pulse durations of 2.3ps, 1.5ps and 0.9ps respectively for the samples with interaction lengths of 2µm, 50µm and 200µm. These results confirm the relationship between the interaction length and the optical nonlinearity; however, it must be pointed out that increasing the length of the device also led to an increase of the insertion losses. Figure 2 (d) shows the output pulse train, the laser operated in its fundamental repetition rate of 5.26MHz.

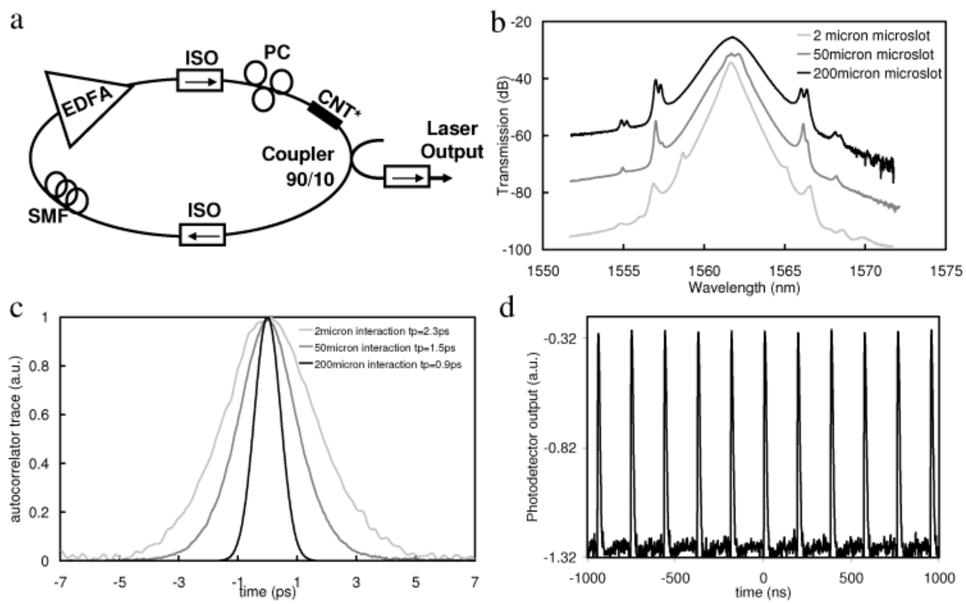


Fig. 2. (a) Set-up of the all-fiber passively mode-locked ring fiber laser. EDFA, Erbium doped fiber amplifier; SMF, single-mode fiber; ISO, isolator; PC, Polarization controller. (b) Optical Spectra from the ring cavity laser. (c) Autocorrelator trace for three microfluidic devices filled with CNTs. By increasing the interaction length between the nonlinear media (CNT) and optical field shorter pulse durations are achieved. (d) Pulse train of measured with a photo-detector.

In previous literature, researchers employ evanescent field interaction as the means to increase the interaction length with the CNTs. Those approaches included the use of D-shape fiber [15,16], taper fiber [11, 17] or hollow core optical fiber [12]. By employing this

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fabrication method, we can also operate with evanescent field interaction using the flexibility of femtosecond laser fabrication, by locating the CNT-filled microslot adjacent to the core, rather than crossing the core. In this work, we fabricated a microslot less than 1 micron away from the core such as shown in Fig. 1(b). The geometry of this structure and hence its performance is analogous to that of the D-shape fiber coated with CNT, thus it was strongly polarization dependent. This polarization dependence rises from the asymmetry introduced with the microslot, one state of polarization interacts strongly with the microslot and the CNT while in the orthogonal state of polarization, interaction with the CNT is at a minimum. Once the polarization is well aligned, self-starting passively mode-locked lasing could be observed. Using the same pump power as for the direct interaction SA, the output power of the laser using the evanescent field SA was 12dBm. Figure 3(a) shows the laser output of the ring cavity fiber laser using this device. The autocorrelator trace yields a pulse duration of 1.3ps assuming that a $sech^2$ pulse shape, as shown in Fig. 3(b). The overall insertion losses for this device were 1.2dB. Compared to the D-shape fiber approach proposed in [15, 16], this approach offers increased control over parameters such as the CNT concentration, interaction length and the distance between the core and the CNT. Due to its structure, it is also more robust and robustness to mechanical damaged thus it is a suitable device for next generation ultrafast all-optical switches [16].

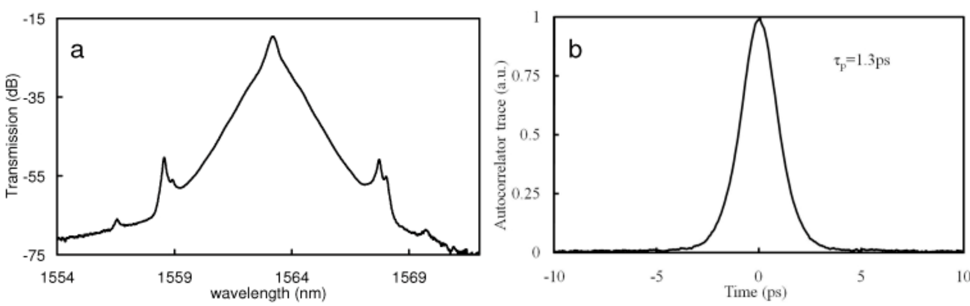


Fig. 3. (a) Optical Spectrum when using a microslot inscribed out of the core (evanescent interaction). (b) Autocorrelator trace yielding pulse duration of 1.3ps.

The method here reported is an attractive alternative to devices that exploit evanescent field interaction between the CNT and the optical field. The flexibility and high level of control of the fabrication process allows a very accurate control over the separation between the core and the CNTs. Since only a small part of the cladding is removed from the fiber, these devices are more robustness and easier to handle than D-shape or taper fiber based CNT-SA. Finally, since the microslots are filled with a CNT solution, the CNT concentration levels can be easily controlled, unlike the optically deposited or sprayed samples where control over the CNT concentration and dispersion quality is difficult to achieve.

In this paper we analyzed the effect of increasing the interaction length of CNT-filled microslots in their application as SAs. We employed microslots of different dimensions engraved into standard optical fibers. This study confirmed that by increasing the interaction length we can increase the nonlinearity of the device and obtain shorter pulse durations. However, there is a trade off between the background losses and the nonlinear effect with the losses also raising with longer interaction lengths. By fabricating the microfluidic channel outside of the core, we can decrease the insertion losses as well as significantly reduce the optical powers endured by the CNT hence the device is less susceptible to optical damage. However in this case, the overall nonlinearity is lower than in the direct interaction design.

As well as the flexibility to control the length and conditions of interaction between the nonlinear media and the propagating light, this method offers compactness, integration and robustness against mechanical and optical damage. In this paper, we only investigated the performance as a factor of the length of the microslots. There are however several other parameters that can be optimized towards more efficient operation, in particular, the thickness

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of the microslot within the fiber core, the CNT concentration levels and the position of the microslot with respect to the core.

## 4. Conclusion

We proposed a simple method to incorporate the CNTs directly into an optical fiber. The flexibility of femtosecond laser microfabrication allows the fabrication of structures that exploit either a direct interaction (where the CNTs are deposited directly in the core of the optical fiber) or evanescent field interaction. The performance of several CNT-filled in-fiber microslots of different geometries was investigated. Self-starting passive mode-locked operation was achieved with all samples and a direct correlation between interaction length of the propagating laser pulses with the CNTs and the nonlinearity of the device was confirmed. The method offers an attractive alternative to other methods consisting on D-shape or tapered fibers employed to increase the interaction length of CNT devices due to the high level of control over the fabrication parameters, the compactness and integration into the optical system and the ability to establish direct interaction with the peak power of the propagating wave.

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