WA4-4

# Mode-locking Using Right-angle Waveguide, Based Nanotube Saturable Absorber

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**Abstract**

**We report passive mode-locking of an Er-doped fiber laser using carbon nanotubes deposited on the facet of a right-angle optical waveguide.**

## I. Introduction

Single wall carbon nanotubes (SWNTs) and graphene based saturable absorbers (SAs) are excellent passive mode-lockers because of their sub-picosecond recovery time [1,2], broad operation range [3,4], low saturation intensity [5,6], low cost [5] and ease of fabrication [3-14]. A variety of techniques have been implemented in order to integrate SWNTs and graphene into lasers [8]. Evanescent field interaction [15,16] can preserve the alignment-free waveguide format of a variety of laser designs [8], e.g. waveguide [17] and semiconductor [18] for high power/energy pulse generation. This technology can also enable compact lasers with GHz repetition rates [14]. Here we demonstrate a new integrated waveguide method for SWNT based evanescent interaction devices. Mode-locking using such SWNT devices is also reported.

## II. Device Fabrication

Waveguides are inscribed in a 30x10mm$^2$ glass substrate (Corning EAGLE 2000) using a master-oscillator power-amplifier fiber laser (IMRA FCPA µ-Jewel D400) [19]. The laser has ~400fs pulse duration and 1047nm central wavelength. The repetition rate is 500kHz. The pulses are focused to 350µm below the surface using a 0.4NA aspheric lens. Waveguides are formed by translating the substrate using automated x-y-z stages. The waveguide cross-section is defined by a multiscan technique, where each waveguide is formed by 20 scans laterally offset by 0.4µm [20]. The optimal low loss inscription parameters are 230nJ and 8.0mm.s$^{-1}$.

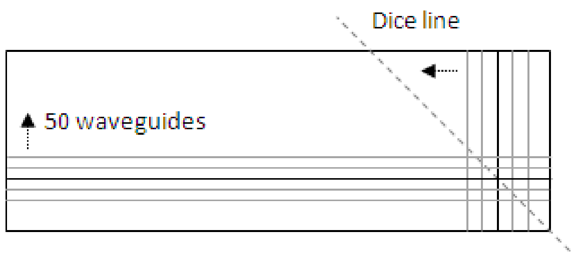


*Fig. 1 Waveguide layout and dicing location.*

A series of 50 orthogonal waveguides are inscribed with vertical and horizontal pitches of 100µm and 102.8µm, as for Fig.1. These lie at an angle of 45.8°. After inscription, the substrate is diced and polished at 45° as shown in Fig.1. The small difference in angles between dicing and line of waveguide intersections ensures that one apex lies within 1µm of the polished facet, resulting in efficient coupling via total internal reflection. In addition, the facets through which the waveguides emerge are ground and polished to remove aperturing effects of the inscription beam. Measurements performed with a broadband ASE source and butt coupling SMF-28 fibers, yield a total optical loss of~1dB.

Ultra-compact lasers, are interesting for a variety of applications [17] and at the focus of an increasing research effort [8,11]. An important role in the device miniaturization is played by the ease of SA integration [8,11]. Waveguide based lasers are suitable for device compactness [8,11]. SWNTs [8] and graphene [11], have the advantage of integration scalability, which combined with waveguide formats can lead to ultra-compact devices. Here, we use a simple SWNT drop-casting approach, showcasing the potential of SA integration.

For our experiment, we use an Erbium-based fiber ring laser, incorporating a waveguide described above (Fig.1). To match the operation wavelength of our laser, we use HiPCo (Hi Pressure Carbon Monoxide) SWNTs[18] with 1nm mean diameter. SWNTs powder (~2mg) is first ultrasonicated in deionized (DI) water with Carboxyl methylcellulose (CMC) polymer for 1hr, followed by 2hrs ultracentrifugation at 35,000rpm to remove the large aggregates. The supernatant is then decanted after the ultracentrifugation process[21]. Fig.2(a) shows the absorption spectra of the HiPco-CMC composite with a peak, due to $E_{11}$ excitonic transition[22], centered at~1.3µm(Fig.2). A single drop of SWNT composite, is

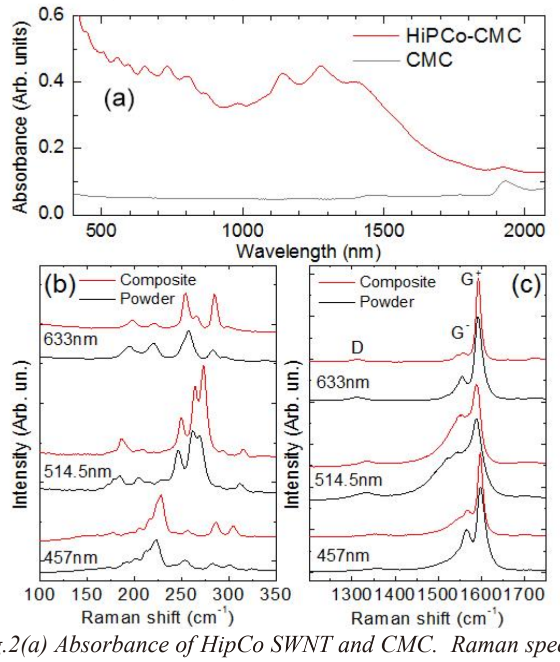


*Fig.2(a) Absorbance of HipCo SWNT and CMC. Raman spectra of HiPCo SWNT at 457,514,633nm for powders (black lines) and dispersions (red lines) in the (b) RBM and (c) G peak region.*

then placed on the angled facet of the substrate and dried over 24hrs. The Raman spectra of the drop cast composite, collected at three different wavelengths (457, 514.5 and 633nm), show similar G$^+$/D intensity ratio compared with the powder, meaning that our procedure does not induce defects. Moreover, from the analysis of

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the RBM[23] and G peak position and lineshape we estimate that the SWNTs' diameter is in the 0.68-1.48nm range, in agreement with the optical absorption.

## III. LASER SETUP AND RESULTS

An Erbium-based fiber ring cavity is formed as shown in Fig.3. The inclusion of an isolator ensures unidirectional operation and a polarization controller matches the round-trip polarization state. An index matching fluid (Decane) is used to reduce reflections between the fiber and substrate facets. Fig.4 shows the spectrum of the mode-locked laser centered at 1556.5nm and with a full-width-half-maximum spectral width of 2.6nm. Assuming a transform limited sech$^2$ pulse, the estimated pulse duration is ~1ps.

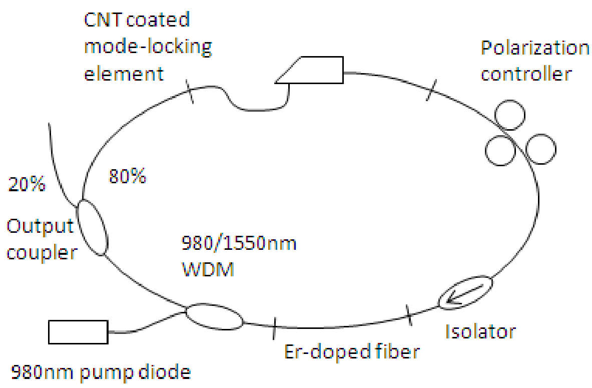


*Fig. 3 Schematic of the mode-locked laser.*

In contrast to previous fiber-based evanescent mode-lockers[15,16], our integrated waveguide device has a number of advantages. E.g., side-polished fiber based devices typically require high-precision polishing and optical monitoring to expose an extended region (~6mm) close enough to the fiber core to achieve sufficient non-linear absorption[16]. As described above, the variation in our horizontal and vertical waveguide pitches removes the need for precise control of polishing. An additional benefit of total internal reflection at the coated facet is the

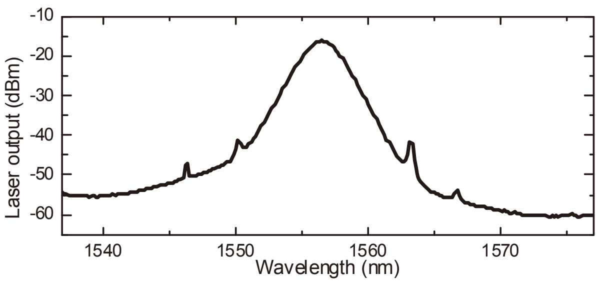


*Fig. 4 Output spectrum.*

increased penetration depth of the evanescent field into the SWNT-SA compared to parallel propagation inside polished fibers[14]. Nonlinear absorption interaction lengths are therefore of the order of the waveguide mode diameter, reducing the required deposition surface area.

## IV. CONCLUSIONS

We demonstrated passive mode-locking of an erbium fiber laser using an integrated, waveguide, SWNT-based mode-locker. This novel design incorporates strong evanescent field interaction due to total internal reflection combined with a simplified fabrication process over previous fiber-based approaches.

## ACKNOWLEDGMENTS

We acknowledge funding from EPSRC grants EP/G030480/1, EP/K01711X/1, EP/K017144/1, ERC Grant NANOPOTS, a Royal Society Wolfson Research Merit Award, The Royal Academy of Engineering, Emmanuel College and King's College, Cambridge, the Newton International Fellowship and the Newton Trust Cambridge.

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