# Mode-locked fiber lasers using vertically aligned carbon nanotubes directly synthesized onto substrates

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**Abstract:** We demonstrate novel passively mode-locked fiber lasers using vertically aligned carbon nanotubes synthesized using the low-temperature alcohol catalytic CVD method. We found that the laser is mode locked at wide slant angle range.

**OCIS codes:** (140.4050) Mode-locked lasers, (160.4890) Organic materials

## 1. Introduction

Passively mode-locked fiber lasers have been used in many applications in various fields, such as optical communications, optical signal processing, two-photon microscopy, laser surgery etc, due to their simplicity and their ability to generate transform-limited optical short pulses in sub-picosecond regimes [1,2]. Such lasers offer superb pulse quality and there is no need for costly modulators as required in actively mode-locked lasers. Instead, a passively mode-locked fiber laser employs a mode-locker, a device that possesses an intensity-dependent response to favor optical pulse formation over continuous-wave lasing. This is usually a fast saturable absorber (SA), such as a semiconductor-based SA, or a fiber-based SA. Amongst these mode-lockers, the semiconductor-based multi-quantum-well (MQW) device, commonly referred as the semiconductor saturable absorber mirror (SESAM), has become the main device used in almost all commercial passively mode-locked fiber lasers.

Instead of SESAMs, we recently demonstrated a saturable absorber incorporating single wall carbon nanotube (SWNT) [3-7], which offers many advantages such as ultra-fast recovery time (<1ps), simplicity, robustness, etc. The SWNT can be directly formed onto the substrates or the cleaved fiber end [7]. However, the SWNTs we have used for SAs was in randomly oriented and entangled forms because it has not been possible to control the alignment of SWNTs until recently. Recently, a part of authors have realized vertically aligned SWNTs grown by a simple chemical vapor deposition (CVD) process [8,9]. This kind of aligned SWNTs will be important and useful for integrated photonic devices and nano photonics.

In this paper, we present novel passively mode-locked fiber lasers using the vertically aligned SWNTs. It is directly synthesized onto quartz substrate. It is expected to imporve the SA characteristics of SWNTs for the mode-locked laser applications.

## 2. Direct synthesis of vertically aligned carbon nanotubes and their absorption spectrum

Vertically aligned SWNTs were grown at 800 ºC and 10 torr using an alcohol CVD process [8,9]. The CVD reaction was catalyzed by Mo/Co bimetal nanoparticles, which were affixed to quartz substrates by a dip-coat method (0.01 wt% Mo/Co acetate). Subsequent annealing in air at 400 ºC oxidized the nanoparticles, preventing catalyst agglomeration in the high-temperature CVD environment. Flowing Ar/$H_2$ (3% $H_2$) during preheating of the reaction chamber reduced the catalyst in order to retrieve catalyst activity before the growth stage. When the CVD chamber reached 800 ºC, the Ar/$H_2$ flow was stopped, followed by the introduction of ethanol vapor. The reaction time was varied in order to observe samples at different stages of growth. The samples were characterized with a Hitachi S-4700 field-emission scanning electron microscope (FE-SEM). Fig.1(a) shows a thick mat of aligned SWNTs on a quartz substrate surface. The advantage of the low-temperature alcohol catalytic CVD method is that it can synthesize SWNTs directly onto various samples, including cleaved end of SMFs.

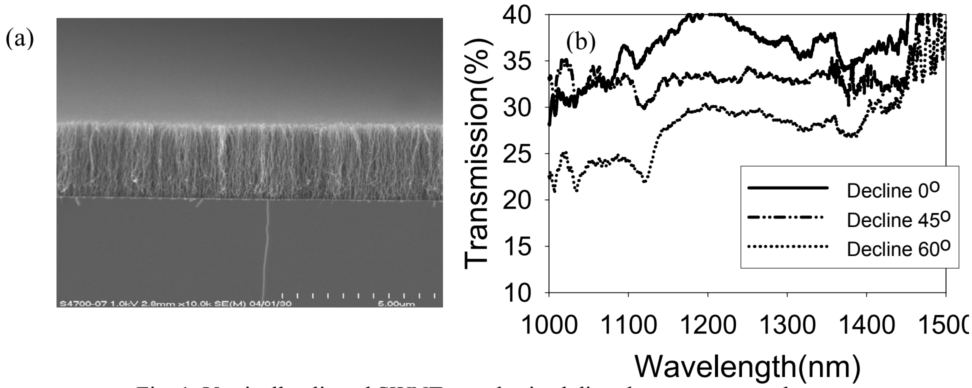


Fig. 1. Vertically aligned SWNTs synthesized directly onto quartz substrate:
(a) SEM image (b) Absorption spectrum

The saturable absorption arises from the energy bandgaps in semiconducting SWNTs. The bandgap energy is determined by the tube diameter of SWNT. Tube diameter of ~1.2nm gives absorption at wavelength around 1550nm. It turns out that SWNTs exhibit little excitonic absorption for lightwave incident in the axial tube direction, therefore vertically aligned SWNT possesses no saturable absorption when the light is incident perpendicular to the substrate, However, saturable absorption can be obtain slanting the substrate at an angle with respect to the incident light. Fig.1(b) shows the absorption spectra of the vertically aligned SWNTs we used for the saturable absorber at slant angles of 0º, 45º,60º. It is a thin layer of vertically aligned SWNTs with thickness of ~3µm, which is synthesized onto the quartz surfaces. In Fig.1(b) the absorption band located around 1500nm, and the absorption become larger as the SWNT sample is slanted.

## 3. Application to the mode-locked fiber lasers

The schematic of the mode-locked fiber ring laser is shown in Fig.2. An erbium-doped fiber amplifier (EDFA) is used as the laser gain medium. The intracavity lasing light is focused onto the vertically aligned SWNT sample through a fiber collimator, and launched back into the fiber cavity via another fiber collimator. The SWNT sample is placed on a rotation stage to allow a variable incident angle. A 10m-long single-mode fiber (SMF) is inserted into the cavity to adjust the intracavity dispersion and to facilitate the pulse formation. A polarization controller (PC) is used to match the round-trip polarization state. 5% of the intracavity lasing light is tapped through a port of a fiber coupler as the laser output, whereas the other 95% is used to feed back into the cavity. Optical isolators are inserted to prevent the back-reflection and to ensure the unidirectional operation.

When the SWNT sample is not slanted, the laser would not start to mode lock even if the EDFA gain was set to the maximum. This confirms that there is no saturable absorption when the light beam is incident to the SWNTs' axial direction. When the SWNT sample is slanted, the saturable absorption arises, and the laser starts to mode lock and produce multiple pulses in a round trip time with small signal EDFA gain around 8.3dB. Once mode locked, the laser sustains mode locked even when the gain is reduced, and it starts to produce single pulse with the EDFA gain around 6.7dB at a fundamental repetition rate of 6.62MHz. The output average optical power is –16.6dBm. The output spectrum, SHG autocorrelation trace, and pulse train of the output mode-locked pulse are shown in Fig.3a, Fig.3b, and Fig.3c, respectively. The autocorrelation trace and spectrum are well fitted by a Gaussian pulse profile. The inferred full-width half maximum (FWHM) width from the autocorrelation trace is estimated to be 1.14ps, whilst the 3dB spectral width is 3.05nm. Fig.4 shows the output pulse powers and pulse widths as a function of the slant angle of the SWNT sample. It is found that the laser operates at wide slant angle range from 1 to 45 degree.

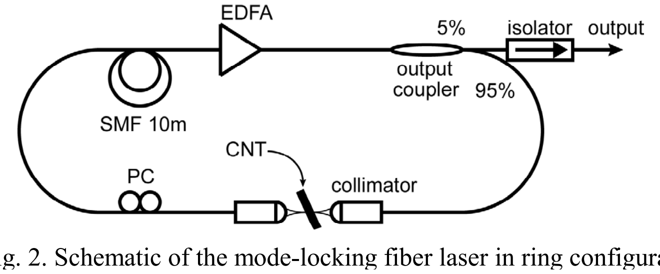


Fig. 2. Schematic of the mode-locking fiber laser in ring configuration

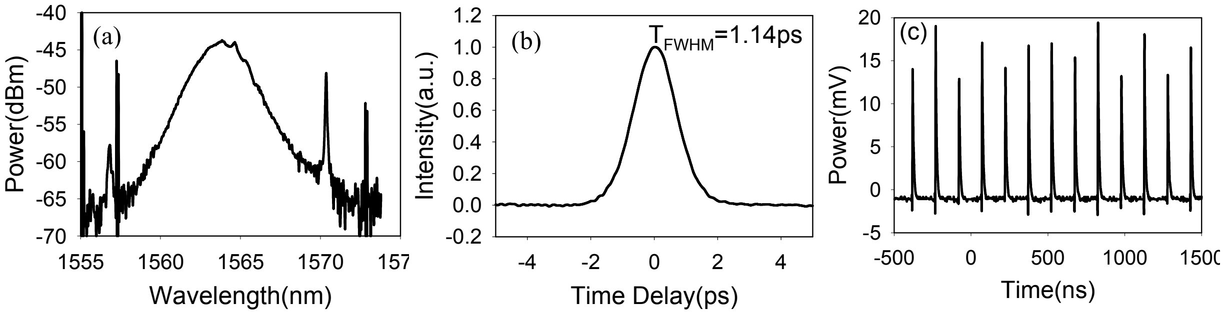

Fig. 3. Ring laser output (a) Spectrum (b) SHG autocorreletion trace (c) Pulse train

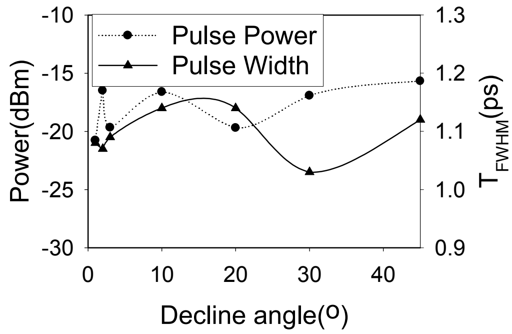

Fig. 4. Pulse power and pulse width as a function of different slant angle of the SWNT sample

## 4. Conclusion

In conclusion, we demonstrated a new mode-locked lasers using vertically aligned SWNTs. Using the low-temperature alcohol catalytic CVD method, high-quality vertically aligned SWNTs were directly synthesized onto quartz substrates. We successfully applied them as a saturable absorber in the mode-locked fiber lasers.

## 5. References


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