Saturable absorbers incorporating carbon nanotubes directly synthesized onto substrates/fibers and their application to mode-locked fiber lasers

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Abstract: We present novel carbon-nanotube-based saturable absorbers. Using the low-temperature alcohol catalytic CVD method, high-quality single-walled carbon nanotubes (SWNTs) were directly synthesized onto quartz substrates and fiber ends. We applied them to the mode-locked fiber lasers.

1. Introduction

Carbon nanotubes, especially single-walled carbon nanotubes (SWNTs), have many interesting and versatile physical properties [1]. However, relatively little attention has been paid for their optical properties until quite recently. Recently, a part of the authors have proposed and demonstrated a "Saturable Absorber Incorporating carbon NanoTube" (SAINT) [2-4] which offers several key advantages such as: ultra-fast recovery time (<1ps), polarization insensitivity, high optical damage threshold, mechanical and environmental robustness, chemical stability, and the ability to operate both in transmission, reflection and bi-directional modes. The device has been employed for noise suppression and laser mode-locking applications at 1550nm wavelength band.

The SAINTs have previously been fabricated through several processes. First, the SWNTs were synthesized by a laser ablation method. After a series of purifying processes, the high-purity SWNTs were dispersed in ethanol and then sprayed onto the surface of quartz substrate. These processes, however, are time-consuming and low-throughput. In this paper, we present a new fabrication technique of SAINT. It is based on the low-temperature alcohol catalytic CVD method [5-7], and can synthesize high-quality SWNTs directly onto the quartz substrates and the single-mode fiber (SMF) ends.

2. Direct synthesis of SAINTs

For a substrate, we used fused quartz with both sides optically polished having a thickness of 0.5 mm. The substrate was submerged into bimetal acetate solution of Mo and Co, then placed in a furnace maintained at 400°C in air to decompose acetates or any other organic residues to form an oxide of bimetallic Mo/Co catalyst. After that, the substrate was placed on a quartz boat, which was then set in a quartz tube inside an electric furnace. Ar/H_2 gas was supplied during the heat-up, stopped at the desired temperature, and evacuated. Subsequently, ethanol vapor was supplied. After the reaction, the electric furnace was turned off and cooled down to room temperature with Ar/H_2 flow.

Fig.1(a) shows the synthesized SWNTs, showing that a uniform SWNT mat with a thickness of a few hundreds of nm was formed. Fig.1(b) is the absorption spectrum of the two stacked substrates. The optical absorption properties of the SWNTs are dependent on the nanotube diameter, and we found an absorption peak around 1450nm corresponding to the bandgap energy of semiconducting E^{S}_{11}, which agrees well with the results of Raman spectroscopy.

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. Figs.2 show the FE-SEM image of the synthesized SWNTs directly onto the cleaved end of SMFs using the same process.

3. Application to mode-locked fiber laser

The schematics of the mode-locked fiber ring laser are shown in Fig. 3. A very short length (40cm) of flouride-based Er-doped fiber (EDF), backward pumped by a 980nm laser diode (LD), is used as the laser gain medium. Use of flouride-based EDF is advantageous because of high gain coefficient [8]. Two optical isolators are inserted to prevent back-reflection in the cavity and to ensure unidirectional operation. The output light from the EDF is launched through a fiber collimator and a focusing aspherical lens onto the SAINT directly synthesized onto quartz substrate. Spot size onto the SAINT is ~10μm. The output light from the SAINT is collected and launched back into the fiber cavity via another set of matching aspherical lens and collimator. A 1m-long dispersion-shifter fiber (DSF) was attached to each collimator, giving a total cavity length of 4.1m. The output of the laser is tapped through a 30% port of a fiber coupler, whereas the other 70% port is used to feed back into the cavity.

With a pump power of around 17mW, the laser self-starts to mode lock and produce single pulses in a round trip time, as shown in Fig.4(a). The fundamental repetition rate is of 50.4MHz, 8-times higher than the previous SAINT-based mode-locked fiber lasers [3][4] due to the use of very short flouride-based EDF. The output average optical power is about −7dBm. The output spectrum is shown in Fig.4(b), showing that the 3dB spectral width is ~ 3.0nm. We also measured SHG autocorrelation trace, and inferred full-width half-maximum (FWHM) width is estimated to be 0.9psec. The resulting time-bandwidth product of 0.34 indicates that the pulses are transform-limited. We also observed that the laser can produce multiple pulses in a round trip time (multiple-pulse mode) by slightly changing the laser configuration. When the SAINT is removed from the laser cavity, it is not possible to mode-lock the laser even with high pump power.

4. Conclusion

We presented a new fabrication technique of SAINT for optical applications. Using the low-temperature alcohol catalytic CVD method, high-quality SWNTs were directly synthesized onto quartz substrates and fiber ends. We successfully applied them as a saturable absorber in the mode-locked fiber lasers.

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5. References

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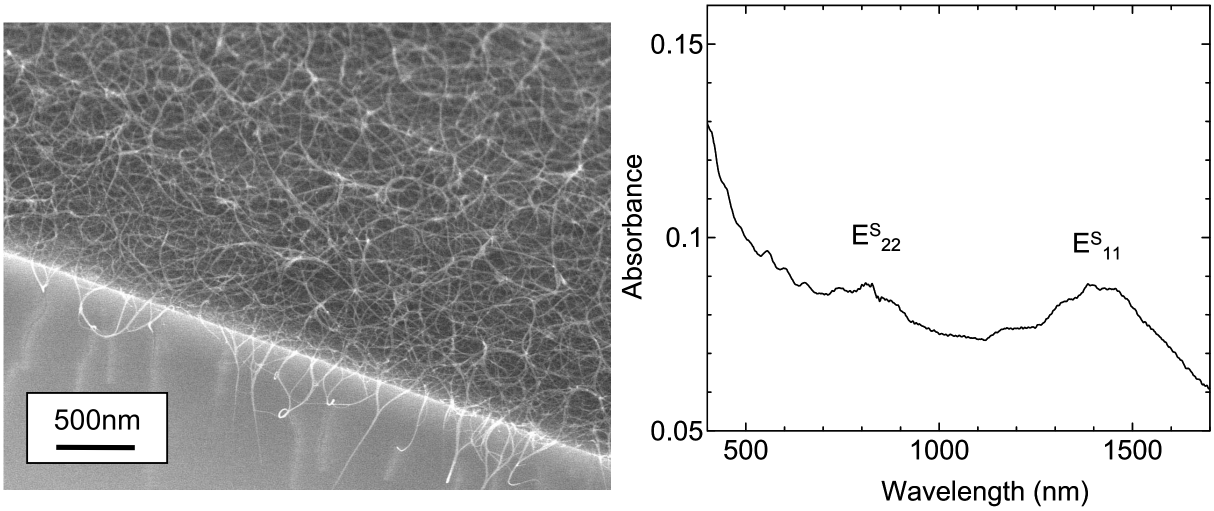

(a) (b)

Fig.1 SWNT synthesized directly onto quartz substrate. (a) FE-SEM image (b) Absorption

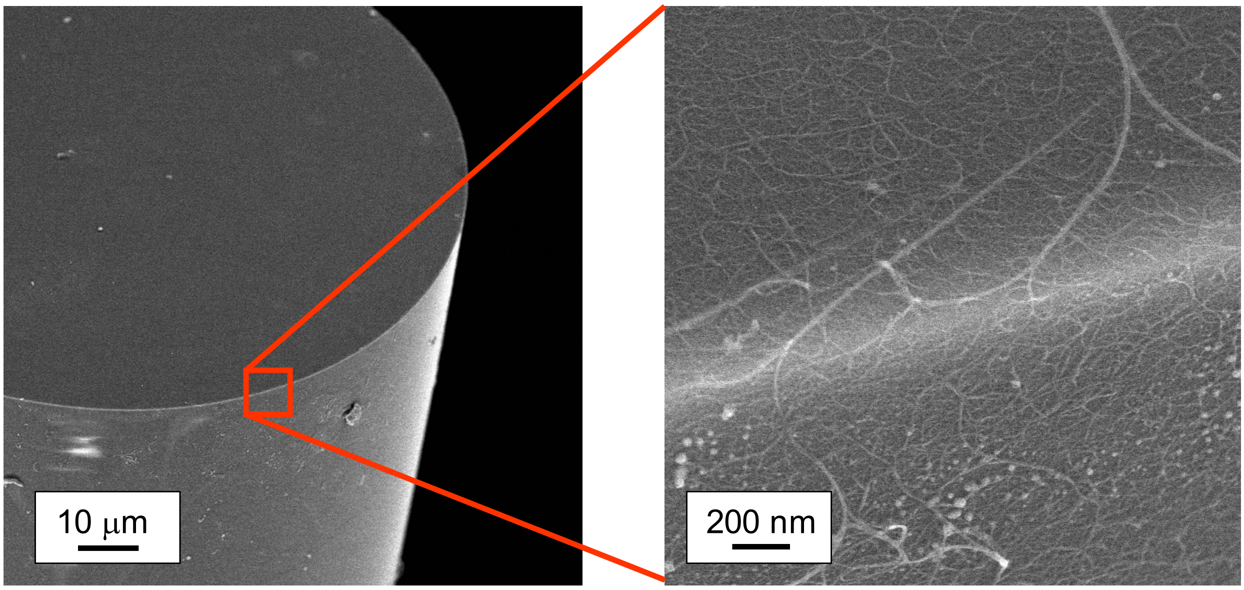

Fig.2 FE-SEM image of SWNT directly synthesized onto cleaved end of SMF.

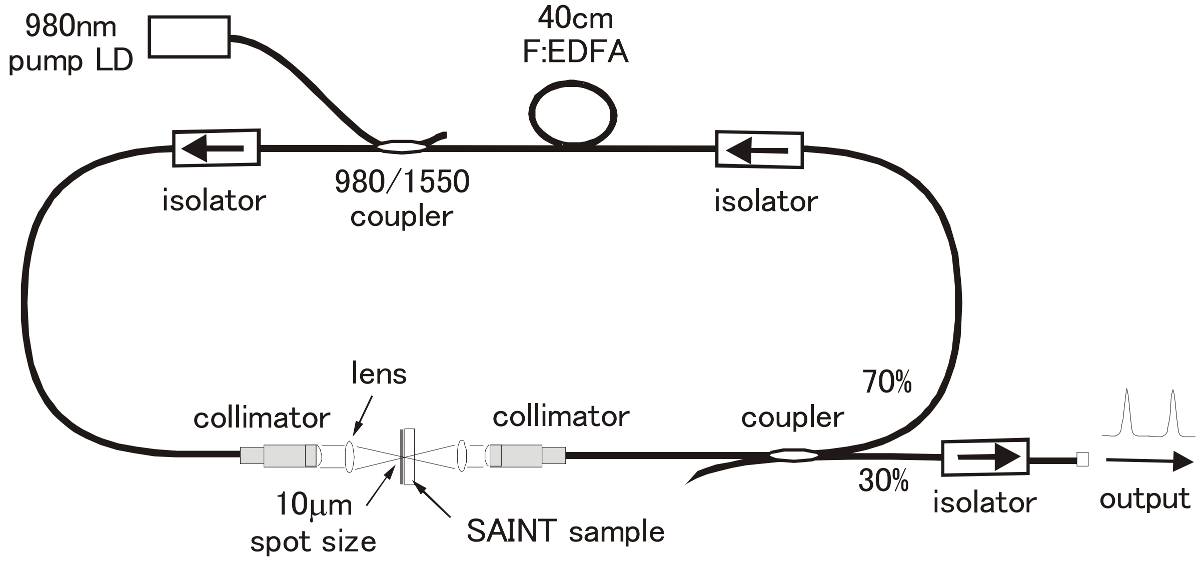

Fig.3 Mode-locked fiber laser with directly synthesized SAINT

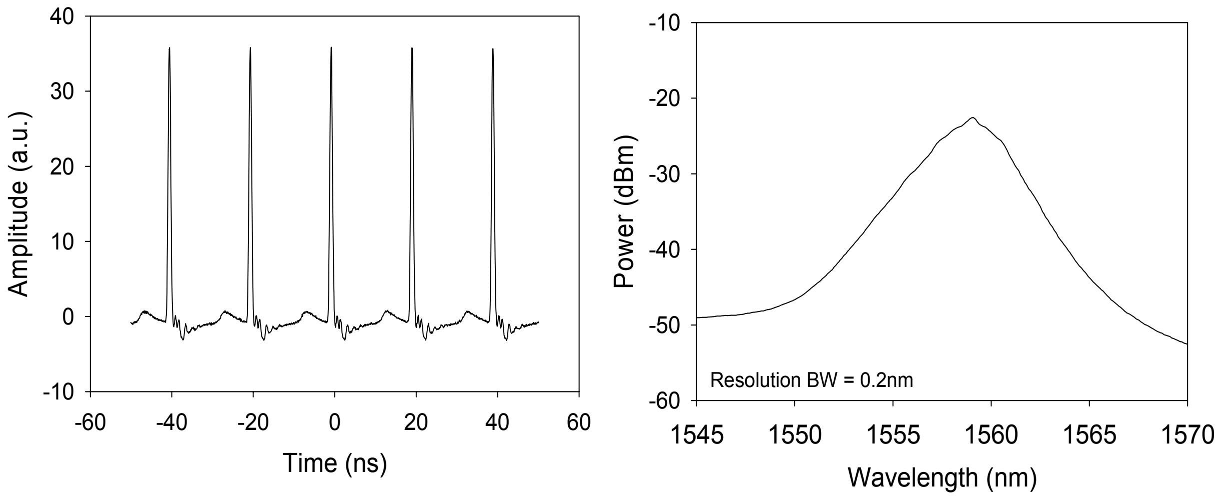

Fig.4 Laser output. (a) Pulse waveform (b) Spectrum