Carbon nanostructures for ultrafast bulk solid-state lasers

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Abstract

Low-dimensional carbon nanostructures are one of the most investigated nanomaterials due to their unique electric and optical properties. In this work, applications of novel saturable absorbers based on single-walled carbon nanotubes (SWCNTs) and graphene for passive mode-locking of different ultrafast bulk solid-state lasers are presented.

Keywords : Carbon nanotube Graphene Mode-locking

1. Introduction

Recently, carbon nanostructures have been successfully used as saturable absorbers in ultrafast fiber and bulk solid-state lasers. While the widespread semiconductor saturable absorber mirrors (SESAMs) provide spectrally narrowband coverage and require complex manufacturing processes with additional post-treatment to reduce response times [1], single-walled carbon nanotube saturable absorbers (SWCNT-SAs) exhibit broadband absorption with quite large third-order nonlinearities and require relatively simple manufacturing processes. An additional advantage of SWCNT-SAs is that their absorption band can be controlled by varying the diameter and chirality of nanotubes, and hence, the wavelength coverage can be engineered within a broad spectral range between 800 nm and 2 μm. To date, investigations on passive mode-locking with SWCNT-SAs were mostly restricted to fibre lasers because their single-pass gain is much higher than in bulk solid-state lasers and therefore they can easily tolerate large non-saturable losses. However, output powers of the mode-locked fibre lasers appear to be intrinsically limited. The reported values were in the mW range. To achieve higher output powers often required for applications, one has to switch to bulk solid-state lasers. For SWCNT-SAs applicable in ultrafast bulk solid-state lasers, it is mandatory to decrease the losses to the lowest level possible.

In this work, mode-locking of ultrafast bulk solid-state lasers employing SWCNT-SA is presented. Important linear and nonlinear optical characteristics of SWCNT-SAs essential for ultrafast mode-locking will be shown with the results on SWCNT-SA mode-locking of different bulk lasers at different wavelengths. Additionally, saturable absorbers based on graphene as novel ultrafast mode-locking device are introduced.

2. Device Fabrication

For fabrication of SWCNT-SAs, differently grown SWCNTs were used as starting materials. The dried SWCNTs were dispersed in dichlorobenzene (DCB) with ultra-sonication process. The SWCNT dispersion was subsequently mixed with polymethyl methacrylate (PMMA) solution and deposited on substrates by spin-coating process [2]. Uncoated quartz substrates were used for deposition. Alternatively, SWCNT layer could be directly deposited on commercial highly reflecting dielectric mirrors for manufacturing reflective devices. The large-area graphene layers were synthesized by chemical vapour deposition (CVD) of methane gases on Cu foils [3]. After spin-coating the graphene film with PMMA, the underlying Cu foil was etched by aqueous $FeCl_3$ solution. Subsequently, the graphene layer supported by PMMA was transferred on to a quartz substrate, and dried on a hot plate at 80˚C. Finally, acetone was used to remove the PMMA layer. The size of the graphene layer on the substrate was about 1.2×1.2 cm^2. Figure 1 shows the typical transmission spectra of SWCNT- and monolayer graphene-based saturable absorbers fabricated.

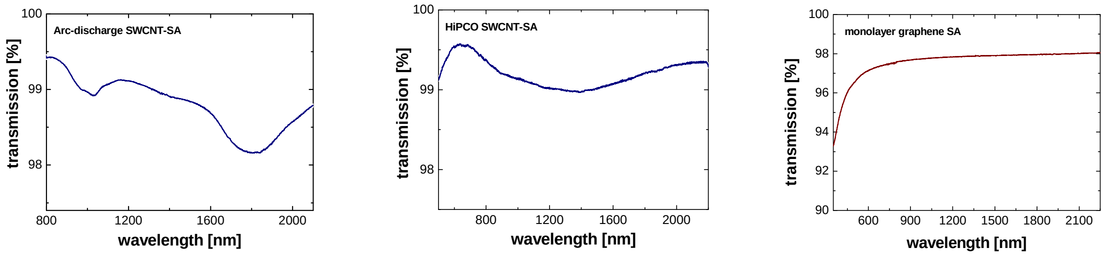

Figure 1: Typical transmission spectra of Arc-discharge and HiPCO SWCNT saturable absorbers and monolayer graphene saturable absorber

3. Mode-locking of Ultrafast Solid-State Lasers

The first demonstration of bulk solid-state laser mode-locking with a SWCNT-SA was demonstrated with a Er/Yb:glass laser near 1.5 µm [4]. This result motivated further mode-locking investigations on other bulk lasers in other spectral regions. Recently, we demonstrated SWCNT-SA mode-locking of Yb-doped bulk lasers in the 1 µm range and of Cr:forsterite and Cr:YAG lasers near 1.25 and 1.5 µm, respectively, which delivered ~100 fs pulses [5-8]. We also achieved SWCNT-SA mode-locked operation of a Tm-doped KLuW and YLF lasers in the wavelength range around 2 µm [9]. We could successfully demonstrate high-power passive mode-locking of a Ti:sapphire laser employing a SWCNT-SA specially designed and fabricated for wavelengths around 800 nm. Mode-locked pulses as short as 62 fs with output powers as high as 600 mW were achieved. The nonlinear response of SWCNT-SAs showed a nearly instantaneous response of < 200 fs and a slow exponential decay of < 2 ps. These responses correspond to the intraband and interband recovery times, respectively. Most recently, monolayer graphene was also used as a novel saturable absorber which exhibits similar nonlinear optical properties and enables stable mode-locking near 800 nm and 1.25 µm. Detailed characteristics of the devices and the mode-locked laser operations at different wavelengths will be shown in the present work.

4. Conclusion

In conclusion, high-quality SWCNT- and graphene-based saturable absorbers were fabricated and applied for mode-locking of different ultrafast bulk solid-state lasers. Such novel passive switching devices based on low-dimensional carbon nanostructures provide not only cheaper and simpler solution for manufacturing in a reproducible manner, but also possess very attractive properties such as low saturation fluence, high damage threshold, and extremely fast relaxation, which make them a promising alternative for replacing semiconductor-based SAs.

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