ENHANCING THE PERFORMANCE OF GRAPHENE OXIDE SATURABLE ABSORBERS BY ADDING CHROMIUM AND TITANIUM TO YTTERBIUM DOPED Q-SWITCHED FIBER LASER

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Paper Summary

We show that the addition of chromium to a graphene oxide Q-switched laser leads to a reduction in the duration of the pulses from 9.4 μs to 3.5 μs.

Introduction

The discovery of graphene [1] has revolutionized different areas in science and technology: graphene is now being used as a platform in applications ranging from relativistic condensed matter physics to ultrafast transistors. The one-atom-thick allotrope of carbon behaves like a zero bandgap semiconductor with properties such as very high electron mobility, strong nonlinear Kerr effects, high thermal conductivity, saturable absorption and high mechanical strength [2].

Applications in photonics and optoelectronics are now starting to emerge: saturable absorber in pulsed lasers [3], ultrafast optical modulators [4] and ultrafast photodetectors [5] (with electrical bandwidths above 20 *GHz*) have been demonstrated in practice. Moreover, graphene may realise the long dream of integration of nanometric electronic and optical devices leading to devices that can operate at high electronic speeds and over very large optical bandwidths.

In spite of these emerging applications, one of the main obstacles of using graphene in optical devices is the weak absorption of graphene [6]. A typical graphene layer absorbs about 2.3% of the incident light. Adding multiple layers of graphene can lead to higher absorption, but a stronger interaction is achieved by adding metallic layers as suggested by Capasso's group at Harvard University [6].

Going in a similar direction, we study the effects of adding a very thin layer of chromium or titanium to graphene oxide layer in an ytterbium doped Q-switched fiber laser: in the case of chromium, we show that the modulation depth of the saturable absorber increases considerably and, consequently, the duration of the pulses can reach sub-microseconds, making it attractive to practical applications.

Analysis and description of the fabrication of the saturable absorber

We have purchased graphene oxide in powdered form from a local vendor (Kemix company). The main difference between graphene oxide and pristine graphene is that graphene oxide has additional atomic bonds to oxygen and hydrogen atoms, but it is cheaper to fabricate and more prone to mass production [7]. The vendor specified that the sample had less than 1% of oxygen and each platelet contained (on average) six graphene layers.

Graphene oxide powder is initially dispersed into isopropanol (*IPA*) and then mixed in an ultrasound bath until a uniform solution is produced and platelets are formed. The optical fiber is then dipped into the solution and the platelets are attached to it by thermophoresis. Whenever chromium or titanium is added to the fiber end, it is deposited by using an electron beam evaporator [8].

In order to understand the effect of adding chromium to the optical fiber, we simulated the low power metal absorption by using Finite-Difference Time-Domain method [9,10]. The computational areas are terminated by perfectly matching layers [10] and the metal is modeled as a lossy and dispersive material with multiple resonances [9]. The results are shown in Fig. 1 indicating that chromium has a larger absorption of light for thicknesses between 20 *nm* and 30 *nm*: a small thickness does not allow the metal to significantly absorb light, while larger thicknesses lead to higher reflectivities of the metal. Similar behaviour is presented by adding a titanium layer.

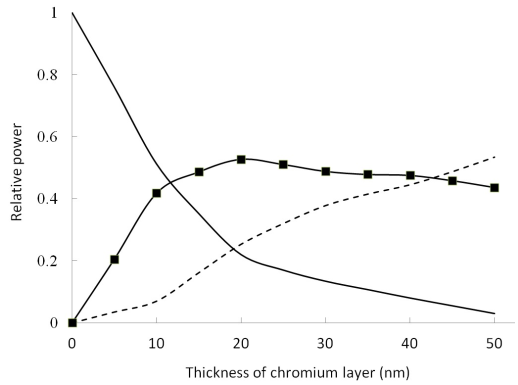

Fig. 1 – Transmissivity (solid), reflectivity (dotted) and absorption (squares) for different chromium thicknesses.

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It should be emphasized that this is the absorption at low power levels: at very high power levels, chromium, titanium and graphene oxide reach saturation and the absorption decreases with power.

Experimental results for chromium and graphene oxide as saturable absorber

The constructed laser is schematically shown in Fig. 2. It consists of a ring ytterbium doped fiber laser, which is pumped by a 980 *nm* continuous wave (*CW*) semiconductor laser array with input power varying from 0 to 1.5 *W*. After passing through a *WDM* coupler, the maximum power is reduced to 800 *mW*. The *WDM* coupler is transparent for 980 *nm* pump wavelength, but blocks the 1091 *nm* radiation that is generated by the ytterbium doped fiber, which has a spot size diameter of 5.5 *μm*. The opposite end of the ytterbium fiber is spliced with 1 *m* of a passive single mode fiber with a core diameter of 6 *μm* to dump the pump radiation. The saturable absorber is placed on the other end of the passive fiber and then connected to another single mode fiber and an optical isolator. The pump laser is switched on-off at a repetition rate of 1 *kHz* and the pulses are observed with a fast detector and power is measured with a power meter.

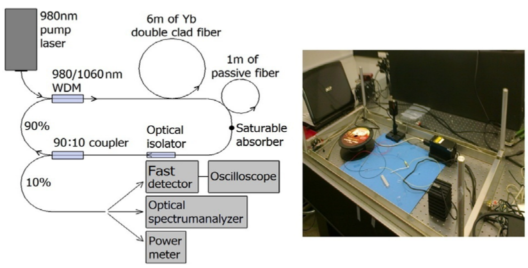

Fig. 2 – Experimental setup.

Initially, only graphene oxide is used as saturable absorber. A typical generated pulse is shown in Figs. 3(a) and 3(b). The duration of the pulse (measured at a pump power of 180 *mW*) is about 9.4 *μs*. At this power level, a single pulse per repetition rate was observed in our experiments: at higher pump power, secondary pulses started to appear in each period. In general, the duration of the main pulse decreases with the pump power as was shown by Ahmad et al. [11,12].

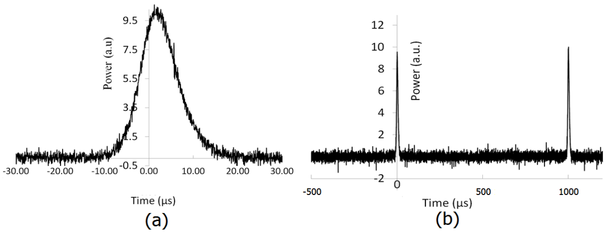

Fig. 3 – (a) Pulse profile for graphene oxide saturable absorber (b) Sequence of pulses at 1 *kHz* repetition rate.

When a very thin layer of chromium is added to graphene oxide, we observe a reduction in the duration of the optical pulses as shown in the plot in Fig. 4 for similar levels of pumped power. As can be observed in Fig. 4, the duration of the pulses reaches a minimum when a 30 *nm* thick layer of chromium is added to graphene oxide: the duration of the pulses is reduced from 9.4 *μs* to about 3.5 *μs*. This minimum can be explained by the fact that the maximum modulation depth of the saturable absorber occurs at a thickness of 30 *nm*. Overall, the addition of chromium increases the low power absorption of graphene oxide platelets from about 12% to more than 50% leading to a considerable reduction in the duration of the Q-switched pulses.

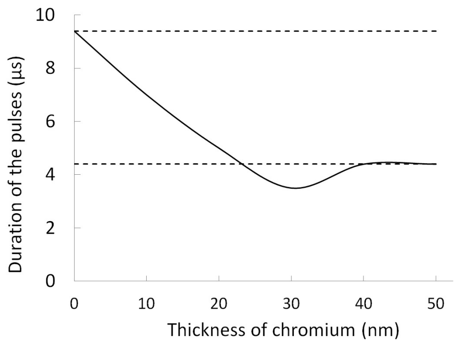

Fig. 4 – Pulse duration for different chromium thicknesses.

The average circulating power for these lasers is shown in Fig. 5: although the thin layer of chromium increases the losses, the laser characteristics are not considerably different from each other. The average circulating power is measured by using a power meter.

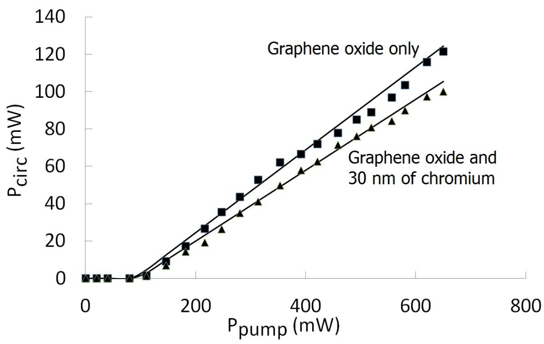

Fig. 5 – Average circulating power (P_{circ}) as a function of the peak pump power.

In our experiments, we have reached pulses with duration lower than 800 *ns* for the ring laser with chromium and pump power P_{pump} =400 *mW*. Each pulse exhibited a series of spikes possibly indicating a transition from Q-switching to Q-switched mode locked regime [13]. In addition to that, several pulses per repetition rate started to appear.

Experimental results for titanium and graphene oxide

Similar experiments are conducted for a combination of titanium and graphene oxide materials. Although titanium lacks the distinctive saturation properties of chromium, it can still be used as an absorber because of its lossy nature. Numerical simulations show that depending on metal thickness, titanium absorption varies from 30% (5 *nm*) to 40% (50 *nm*), approaching chromium values (29%-38%). In our experiments, we observe an increase of pumping power threshold for titanium and graphene oxide combination compared to the combination of chromium and graphene oxide. At the same time, the recorded averaged circulated power is decreased by approximately 10%. This can be attributed to absorption of titanium being generally larger, but having significantly higher saturation intensity. In other aspects titanium qualitatively behaves similarly to chromium: as the pump power increases, the additional pulses start to appear and the first pulse becomes slightly shorter.

Experimental measurements show that the pulse duration for 30 *nm* thick titanium layer is about 9.33 μs, which is close to 9.4 μs for only graphene oxide absorber. When 30 *nm* of titanium is added to graphene oxide, the duration of the pulse reduces to 8.32 μs. Thus, the pulse shortening for this case is about 11%, while for chromium added to graphene oxide it is almost 63%. The changes in the pulse time profiles are vizualized in Fig. 6, where solid curve corresponds to original graphene oxide data, and dotted curves correspond to addition of metals.

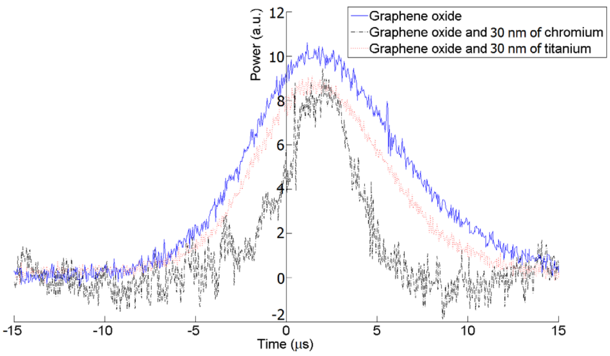

Fig. 6 – Peak power pulse profiles for different combinations of saturable absorbers.

Conclusions

In this paper we studied the performance of the ring ytterbium laser with a composite saturable absorber made of mixture of chromium and graphene oxide. The shortest pulses of 3.5 μs are achieved for 30 *nm* thickness of metal. This could be explained by changes in graphene oxide's absorption properties because of the presence of metal. The similar effects are observed for titanium and graphene oxide case, however this combination results only in a pulse shortening of about 11%.

We also observed the further shortening of pulses in a composite metal-graphene oxide absorbers after increasing the pump power. However the practical use of this effect is limited by the simultaneous generation of additional secondary pulses.

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