Synchronously coupled fiber lasers and sum frequency generation using graphene composites

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Abstract: Graphene mode-locked and self-sychronized fiber lasers are used for sum-frequency mixing in a graphene-polymer composite.

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1. Introduction

Graphene is an attractive platform for next-generation optoelectronic and photonic technologies [1]. Third-order $\chi^{(3)}$ nonparametric processes associated with saturable absorption [2] in graphene [3, 4], have been extensively used for mode-locking of ultrashort pulse lasers [4–8], due to graphene's ultrafast recovery time [3], broadband operation [5,9], ease of fabrication [4, 8], and integration [1]. Graphene also exhibits ultrafast $\chi^{(3)}$ parametric response [10], which coupled with its intrinsic gapless linear band dispersion [1] could in principle offer full-band, tunable frequency mixing processes [10].

Here, we show that two lasers can be passively mode-locked and self-synchronized using a graphene-based saturable absorber (GSA). We use our source of synchronous ultrashort pulses to generate a sum-frequency signal in an extra-cavity sample of the same graphene film. A strong, coherent emission is generated ∼800 nm, through degenerate four-wave mixing (FWM). Our results highlight the potential of graphene-based composites, both as broadband ultrafast switches and as dispersionless nonlinear wavelength converters.

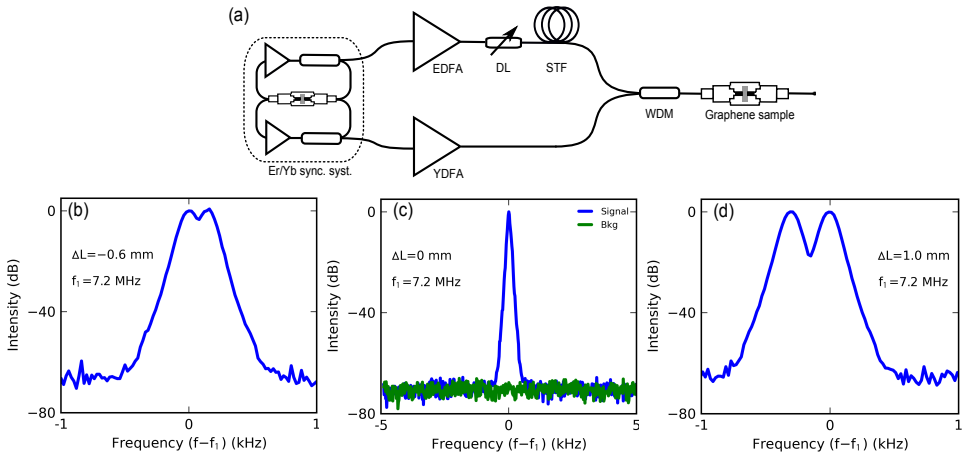

Fig. 1. (a) Setup for synchronization system and sum-frequency generation. (b), (c) and (d) Fundamental radio frequencies of the Er- and Yb-lasers, corresponding to a cavity mismatch of ΔL=-0.6 mm, ΔL=0 mm and ΔL=1.0 mm, respectively.

2. Results

The experimental configuration is shown in [Fig. 1(a)]: synchronization between the Er and Yb lasers is achieved using a graphene-polymer composite SA [4]. Synchronous operation is confirmed through measurement of the radio frequency (RF) spectrum [Fig. 1(c)], for cavity detuning $> \Delta L = \pm 0.5$ mm, corresponding to the locking-range of the cavity. The dual-peaked structure in the RF trace [Figs. 1(b,d)] indicates that the laser no-longer operates in a synchronous mode [11]. The dual output is independently amplified and subsequently recombined using a wavelength

division multiplexer (WDM) before being coupled through a second piece of the same GSA. Walk-off between the synchronous pulses in the independent amplifiers, due to group velocity dispersion (GVD), is compensated by balancing the optical path lengths. A ∼12.5 m length of single-mode fiber (SMF) is inserted into the Er-arm, such that a fiber pigtailed optical delay line (DL), with a total delay of 300 ps, can be employed to convolve the pulses at the GSA, thus achieving complete temporal overlap and the strongest nonlinear interaction. In addition to balancing the optical paths, the length of SMF acts as a stage of high-order soliton compression for the pulses in the Er-arm (confirmed through simulation). This leads to an increase in the pulse peak-power, and a down-shifting of the pulse center frequency to ∼1601 nm through self-Raman interaction [2].

Figures 2(a,b) plot the measured spectra after the GSA. A resonant spike in emission can be seen at $\lambda_e = 796.1$ nm, which confirms the generation of coherent parametric emission. To confirm that the emission at λ_e is generated by the mutual interaction of waves at λ_p and λ_s, the parametric signal is monitored as a function of delay between the two mixing pulses. The trend is shown in Fig. 2(c). The contrast against the diagnostic noise floor of the spectral component at λ_e is maximal around zero delay, and decays with increasing separation following a profile that can be approximated by a sech^2 lineshape. This is comparable to performing the cross-correlation of the two synchronous pulses and can have implications for the characterization of wideband ultrashort pulses due to the dispersionless nature of graphene [1]. To confirm that the response of graphene governs the interaction, the same experiment is conducted with a pure polymeric film. No emission is observed at energy matched wavelengths [see Fig. 2(a)].

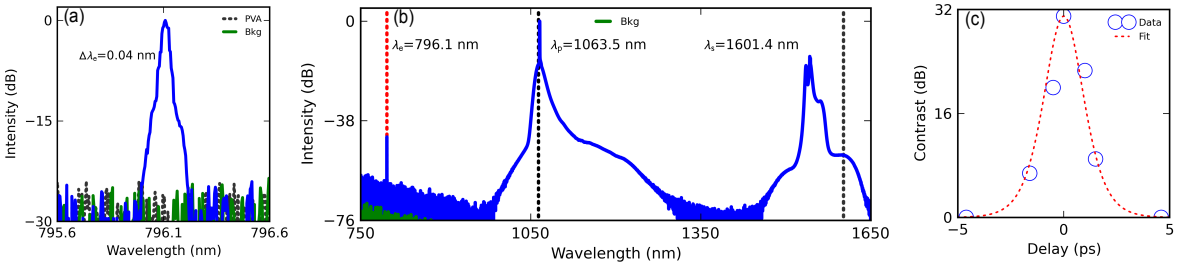

Fig. 2. Measured optical spectra after the extra-cavity GSA. (a) A close-up of the generated emission, at the energy matched wavelength of $\lambda_e = 796.1$ nm. (b) Full span showing the pump, signal and emission lines. (c) Contrast of the generated parametric emission as a function of delay between the excitation pulses.

3. Conclusions and outlook

We demonstrated that graphene can perform as a simultaneous passive SA and self-synchronizer. We constructed a two-color picosecond source, then applied it as a pump system to demonstrate sum-frequency generation in an extra-cavity sample of the same graphene-polymer composite film. A coherent mixing signal was generated at ∼800 nm through degenerate FWM. Our results further underline the potential of graphene for ultrafast nonlinear photonic systems.

4. Acknowledgments

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