Tunable Optical Frequency Comb Generation in Fiber Fabry-Perot Cavity with Gate-control Graphene Modulator

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***Abstract*—A gate-tunable graphene optical modulator fabricated on optical fiber tip is designed and experimentally demonstrated, based on which an electrically tunable optical frequency comb generator with configuration of Fabry-Perot cavity is numerically investigated.**

Keywords—graphene; optical modulator; fiber device; optical frequency comb; Fabry-Perot cavity; soliton

I. Introduction

In the field of light manipulation, the zero-gap Dirac cone structure of energy band and tunable Fermi level make graphene an ideal medium for optical modulation through various approaches. Routinely graphene can be integrated with waveguide on chip from side to achieve light-matter interaction [1], which, however, confronts the inevitable coupling loss during connection since the current optical communication systems are comprised of fiber.

Recent decades also see the rapid development of all-fiber-integrated devices. Generally, the combinations of functional 2D materials and optical fiber are realized in two methods: side integration and end-face integration. Side-integration utilizes tapered microfiber [2] or side-polished D-shape fiber [3] for evanescent field interaction. However, this type of integration usually trades insertion loss for modulation depth. Meanwhile, in certain application fields like fiber laser or fiber Fabry-Perot (FP) cavity [4], ultra-compact geometry, moderate-range modulation depth and fine tunability take up more significance since such systems are sensitive to loss. Therefore, end-face-integrated modulator came into light. Earlier work demonstrated dual-electrodes-on-facet configuration, where electric current introduced Joule heat and current-doping to manipulate graphene's Fermi level [5]. Nevertheless, dual electrodes provide only one active channel for applying manipulating signals. Besides, the increased local temperature could bring about instability and damage to the device.

In this work, we report a gate-tunable graphene optical modulator directly fabricated on the tip of optical fiber, which can be summarized as fiber-end-face-integrated graphene field effect transistor mirror (FG-FETM). Optical reflectance of the device is responsively tuned according to gate voltage. Based on the all-fiber electro-optical modulator, an electrically tunable optical frequency comb generator with configuration of fiber Fabry-Perot (FP) cavity is also proposed and numerically demonstrated. The Q-factor of fiber cavity is effectively tuned by an order of magnitude with control of gating voltage, while the output frequency comb regime can be tuned from single-soliton to breathing soliton and multi-soliton with fixed pump power and detuning.

II. Device and Experiments

Fig. 1(a) illustrates the schematic diagrams of fiber FP cavity with FG-FETM. The two end faces of optical fiber are polished first. At one end face, the fiber is coated with distributed Bragg reflection (DBR) film to form one cavity mirror, where another end-polished fiber is aligned to form input and output port. At another end face, twin electrodes are located symmetrically on the two sides of optical fiber core, bridged by patterned rectangular graphene sheet which covers the core for light-material interaction. Layer of dielectric material is deposited on graphene and completely covers the graphene sheet, followed with gate electrode on the top of dielectric layer which also plays the role of another cavity mirror. Light input from the fiber core gets reflected in the device, hence interacts with graphene twice. The dual electrodes of gold serve as source and drain respectively, while the graphene, dielectric (here Al_2O_3 is adopted), and top-gate (reflecting mirror, Cr/Au double layer) constitute a standard parallel-plate capacitor gating model. The theoretical dependence between Fermi-level and gate voltage (V_G) under Al_2O_3 dielectric with thickness of 30 nm and 225 nm is shown in Fig. 1(b), demonstrating monotonicity with increasing gate voltage, which lays the foundation for optical modulation. The optical absorption of graphene can be estimated by [6]

$$A \approx 1\text{-}T - 1\text{-}\,(1 + \pi\alpha\,/\,2)^{-2} \qquad (1)$$

where $\alpha = \sigma / (\pi\varepsilon_0 c_0)$, σ is the conductance of graphene, and c_0 is the light speed in vacuum. For single-layer graphene, the conductance σ can be derived from Kubo formula [7]. The graphene optical absorptance at 1550 nm determined by Fermi-level is shown in Fig. 1(c). The reflectance of Cr/Au mirror is near 100%, so the reflectance of FG-FETM is mainly controlled by graphene.

The method of electron beam lithography (EBL) is introduced into the process of fiber-end-face integration to achieve precise patterning of graphene and microelectrodes, enabling an all-fiber reflecting scheme without spatial coupling loss of light, along with a compact packaging scale

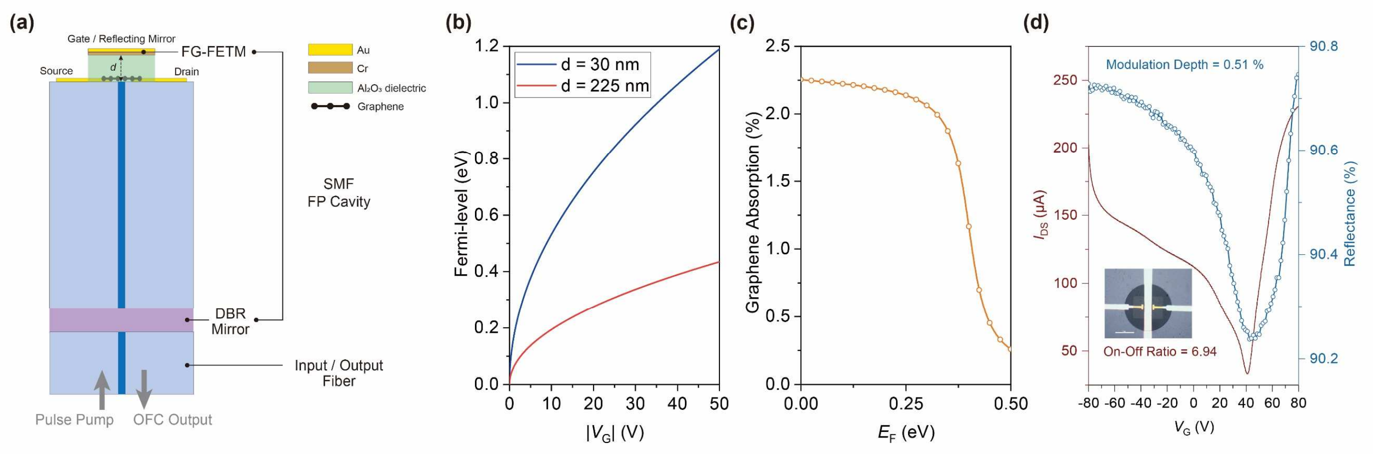

Fig. 1. (a) Scheme of the fiber FP cavity with FG-FETM. (b) The dependence between Fermi-level of single-layer graphene and applied gate voltage. (c) Single-layer graphene absorption under1550 nm when Fermi-level gets tuned. (d) Tunning curves of device reflectance and drain-source current.

to several hundreds of micrometers. Figure 1(d) plots the typical modulation achieved by FG-FETM. Reflectance was monotonically controlled by V_G on both sides of Dirac-point, and the optical modulation depth reached 0.51% along with electrical on-off ratio of 6.94 in experiment. Inset shows the microscopic photo of completed fiber-tip modulator device, where the scale bar is 50 µm.

III. Tunable Optical Frequency Comb

As described in Section II, the cavity structure is promising in generating soliton frequency comb which can be tuned by the modulator. Here we adopt 1 cm fiber cavity length which corresponds to a free-spectral-range of 10 GHz. The input pump is set as pulse with 10 GHz repetition rate matching the cavity resonance, which has a gaussian profile with pulse width of 1.5 ps.

The simulation is based on the FP Lugiato-Lefever equation (FP-LLE) derived in Reference [4], as expressed in Equation (2). E is the optical field envelope, τ_R is the roundtrip time, θ is the pump couple efficiency which is set as 0.001, E_{in} is the input pump field, α is the intracavity loss, δ_0 is the detuning, which is fixed here. The fiber dispersion β_2 is adopted as -22 ps^2/km, with nonlinear coefficient γ = 1 W^{-1}/km. As the intracavity loss α can be tuned by manipulating FG-FETM gate voltage, the Q-factor of the device should be effectively tuned as well. Fig. 2(a) depicts the cavity Q-factor's dependence on graphene's linear absorption, where the value is continuously tuned from 1.2×10^7 to 4.9×10^6 with increased absorption.

$$\tau_R \frac{\partial E(t,\tau)}{\partial t} = \sqrt{\theta} E_{\text{in}} + \left[- \alpha - i\delta_0 - iL\left(\frac{\beta_2}{2}\frac{\partial^2}{\partial \tau^2} - \gamma |E|^2 - \frac{2\gamma}{\tau_R}\int_{-\tau_R/2}^{\tau_R/2} |E|^2 \mathrm{d}\tau \right) \right] E \tag{2}$$

When deal with the LLE, the nonlinear absorption (or saturable absorption) of graphene should also be considered into α. The time-dependent nonlinear loss α_G introduced by graphene can be obtained through [8]

$$\frac{\mathrm{d}\alpha_G}{\mathrm{d}t} = \frac{\alpha_S}{t_r} - \frac{\alpha_G}{t_r}\left(1 + \frac{I(t)}{I_{\text{sat}}}\right) \tag{3}$$

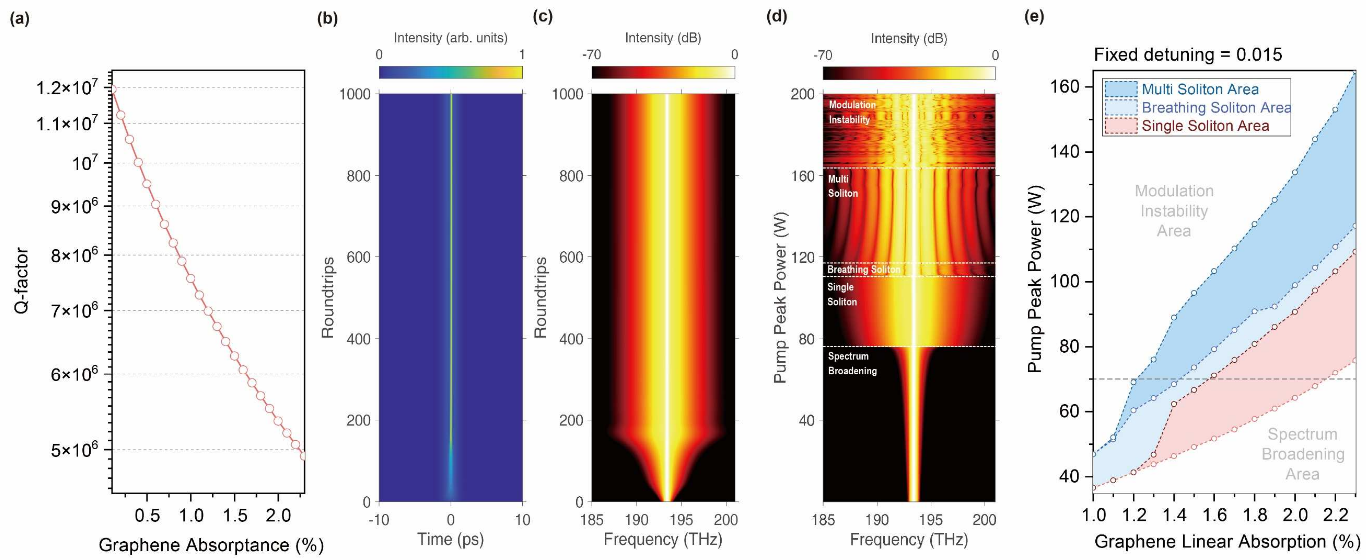

Fig. 2. (a) Q-factor tuning of the fiber FP cavity depending on the graphene absorption. (b) Temporal and (c) spectral evolution of a traditional FP-cavity soliton. (d) Evolution of cavity output comb spectrum with increased pump peak power at fixed detuning. (d) The different soliton regimes map of versus graphene linear absorption and pump peak power.

where α_S is the saturable loss, t_r is the graphene relaxation time, $I(t)$ is the incident optical field intensity, and I_{sat} is the saturable intensity. Equation (3) can be numerically solved by Runge-Kutta method.

Considering all above conditions, the fiber-FP cavity model is simulated numerically. Fig. 2(b) and (c) illustrates the temporal and spectral filed evolution of frequency comb in the fiber FP-cavity where the graphene is not tuned by gate voltage (which means the linear absorptance is about 2.3%). The peak power of input pump pulse is 75 W. The spectrum is vividly broadened due to 3rd order nonlinearity and a stable soliton frequency comb is built after 200 roundtrips. The output soliton comb possesses pulse width of 244 fs and -3 dB bandwidth of 1.47 THz under sech^2 fitting profile.

When the cavity detuning is fixed, if the peak power of pump pulse is scanned, we can obtain multiple steady-state dynamic results. As illustrated in Fig. 2(d), at lower pump peak power, the steady output shows nothing but merely slight spectrum broadening. When pump power reaches the threshold, the output turns into soliton regime precipitously, exhibiting vivid boundary. Thereby the output comes into single-soliton regime. Then with increasing of pump power, the comb splits into multiple solitons but the bandwidth fluctuates randomly, showing breathing-soliton states. By continuously lifting the pump level, the multi-soliton regime becomes stable and evolutes smoothly until the pulse energy goes beyond the limit where the soliton state can no longer be held and the output becomes modulation instability. The boundaries of different output regimes shall be identified by pump power level.

And when the gated graphene is under consideration, the comb evolution process will be different since linear and nonlinear intracavity loss vary. We take different linear absorption values of graphene into equation (2) and the corresponding nonlinear absorption is involved through equation (3), with fixed detuning of 0.015. Simulation results give different regime boundaries under varied gated graphene. The comb regime map versus pump peak power and graphene absorption is obtained as Fig. 2(e). The map is divided as spectrum broadening area, single soliton area, breathing soliton area, multi soliton area and modulation instability area. If we fix the pump power level, e.g., at 70 W (grey dash line), one can find that by solely tuning the graphene the output frequency comb regime will be sequentially shift within 5 different states.

IV. Conclusion

In summary, a novel all-fiber-based gated graphene optical modulator is proposed and demonstrated experimentally, and a tunable frequency comb generator with fiber FP-cavity scheme with end face that based on the modulator is also demonstrated in simulation. The device shows potential in soliton regime control in fields of microcavity combs.

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