All-optical graphene modulator based on optical Kerr phase shift: supplementary material

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This document provides supplementary information to "All-optical graphene modulator based on optical Kerr phase shift," <http://dx.doi.org/10.1364/optica.3.000541>. We give further details on the experiment setup of the modulators, dependence of the modulated output intensity on the signal wavelength, estimation of modulation depth, as well as illustration of phase modulation in a graphene-clad microfiber (GCM). © 2016 Optical Society of America

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1. Experiment setup of the modulator

Fig. S1. Experiment setup of a Mach-Zehnder interferometer (MZI) with a graphene-clad microfiber in one arm for optical phase modulation.

2. Dependence of the modulated output intensity on the signal wavelength

The output intensity from our MZI is given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\varphi_2 - \varphi_1) \quad (\text{S1})$$

$$\varphi_1 - \varphi_2 = \frac{2\pi n \Delta l}{\lambda} + \Delta\varphi', \quad (\text{S2})$$

where I_1 and I_2 are the intensities of the waves from the GCM and the reference arms, respectively, and φ_1 and φ_2 are the corresponding phases of the waves, Δl denotes the path difference of the two arms, λ is the wavelength, and $\Delta\varphi'$ is the optically induced phase shift in the GCM arm. The operation point for phase modulation, described in Fig. 4f, can be set by adjusting either Δl or λ .

3. Estimation of modulation depth

A. For a GCM fiber

From the measured transmittance, we obtained the linear attenuation coefficient of the GCM to be $\alpha_o = 154/\text{mm}$ in the absence of switching light, and $\alpha_p = 146/\text{mm}$ in the presence of a 1.15-W switching pulse. With $T_o = e^{-\alpha_o L}$ and $T_p = e^{-\alpha_p L}$, the modulation depth (MD) is given by

$$\frac{\Delta T}{T} = \frac{T_p - T_o}{T_o} = \frac{e^{-\alpha_p L} - e^{-\alpha_o L}}{e^{-\alpha_o L}} \quad (\text{S3})$$

where L is the graphene coating length.

B. For an all-fiber MZI with phase modulation in its GCM arm

To optimize phase modulation in GCM and MD for the MZI output, we adjust the path difference of the two arms of the MZI to yield a phase difference of $\Delta\phi_0 = \frac{2n+1}{2}\pi$ (n =integers) for the selected wavelength and the input light intensities, I_1 and I_2 , into the GCM arm and the reference arm, respectively, to yield equal output intensities from the two arms, i.e., $I_1 = I_2 T_o$. In such a case (see Fig. S2), the interference output from the MZI has the expression

$$\begin{aligned} I &= 2I_1 \left[1 + \cos \left(\frac{2n+1}{2}\pi + \Delta\phi_M \right) \right] \\ &= 2I_1 [1 \pm \sin(\Delta\phi_M)] \end{aligned} \quad (\text{S4})$$

where $\Delta\phi_M = pL$ is the optically induced phase modulation in the GCM arm. For the experiment described in the main text, we found $p = \frac{0.18\pi}{15\mu m} = 0.012\pi/\mu m$ with a switching pulse peak power of 1.15-W. The transmittances of the MZI without and with the switching light in the GCM arm are, respectively,

$$T_{o-MZI} = \frac{2I_1}{I_1/T_o + I_1} = \frac{2T_o}{T_o + 1} \quad (\text{S5})$$

and

$$T_{p-MZI} = \frac{\pm 2I_1 [1 \pm \sin(pL)]}{I_1/T_o + I_1} = T_{o-MZI} [1 \pm \sin(pL)] \quad (\text{S6})$$

leading to an MD of

$$\frac{\Delta T}{T} = \frac{T_{p-MZI} - T_{o-MZI}}{T_{o-MZI}} = \pm \sin(pL) \quad (\text{S7})$$

4. Illustration of phase modulation in a MZI

Fig. S2. Illustration of phase modulation in a MZI. The hollow and solid points represent the original phase difference and the phase difference under optical pump, respectively, between the two arms of the MZI.