Optics Communications 410 (2018) 604–608

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

All-optical intensity modulation based on graphene-coated microfibre waveguides

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ARTICLE INFO

Keywords:
Graphene
Modulator
Waveguide

ABSTRACT

We investigate graphene-covered microfibre (GCM) waveguides, and analyse the microfibres' evanescent field distributions in different diameters and lengths by numerically simulation. According to the simulation results, we designed a graphene-based all-optical modulator using 980 nm and Amplified Spontaneous Emission (ASE) lasers, employing the microfibre's evanescent field induced light–graphene interaction. We studied the modulation effect that is influenced by the microfibre's diameter, number of graphene layers, and effective graphene length. Compared to a single graphene layer of shorter length, the double graphene layer with longer length presents stronger absorption and higher modulation depth. Using a 2-μm diameter microfibre covered by ~0.3 cm double graphene sheets, we achieved a modulation depth of 8.45 dB. This modulator features ease of fabrication, low cost, and a controllable modulation depth.

1. Introduction

An optical modulator is one of the key components in the gateway between electronic and optical domains. To date, various optical modulators have been demonstrated, such as the electro-optic [1], thermo-optic [2], and electro-absorption [3,4] modulators, which are designed to manipulate amplitude, phase, and the polarisation state of light. Intensity modulators have been applied in optical communications, signal processing, sensing and photodetection [5–8]. The most extensively developed intensity modulators are the electro-optic polymer modulator and silicon core fibre Fabry–Pérot (F–P) cavity based modulator, graphene based top-gate optical modulator and all-optical intensity modulator in a liquid crystal channel waveguide, which perform at modulation depths of 18 dB [9], 10 dB [10], 1.2 dB [11], and an on–off optical power extinction ratio larger than 44 dB [12], respectively. However, these modulators usually have a complicated structure, relatively low modulation efficiency and high cost. Recently, graphene has attracted significant research momentum in the designing of novel optical modulators. Due to its unique electronic structure, photonic properties and carrier transport properties [13–17], graphene is considered an ideal and promising material for optical modulation. The atomically thin crystal alignment and high flexibility make it possible to incorporate graphene with other photonic structures [18,19] (e.g. the microfibre waveguide integrated graphene all-optical modulator) to achieve broadband light–matter interaction.

In this letter, we numerically simulated the mode distribution and found that the evanescent field is strongly influenced by the diameter of the microfibre. According to this property, we designed an all-optical intensity modulator consisting of a single graphene sheet covered microfibre (SGCM) waveguide and double graphene sheet covered microfibre (DGCM) waveguide. The diameters of the microfibres were selected as 2 μm, 4 μm and 6 μm for comparison. A narrow band 980 nm laser and a broadband amplified spontaneous emission (ASE) light in the telecommunication band (from 1527 nm to 1565 nm, 10 dBm power) were used as the pump the light and the modulation light, respectively. The results show that the SGCM and DGCM with a 2-μm diameter exhibit a higher modulation depth than those with a 6 μm diameter, which is consistent with our simulation result. Our method introduces an easily controlled mechanism to realise optical–optical modulation in the near-infrared region, which provides a promising technique for optical signal processing and optical communications.

2. Numerical simulation and GCM fabrication

We numerically simulated the relationship between the evanescent field distribution and the diameters of the GCMs with the RSoft method.

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https://doi.org/10.1016/j.optcom.2017.10.078
Received 6 August 2017; Received in revised form 28 October 2017; Accepted 29 October 2017

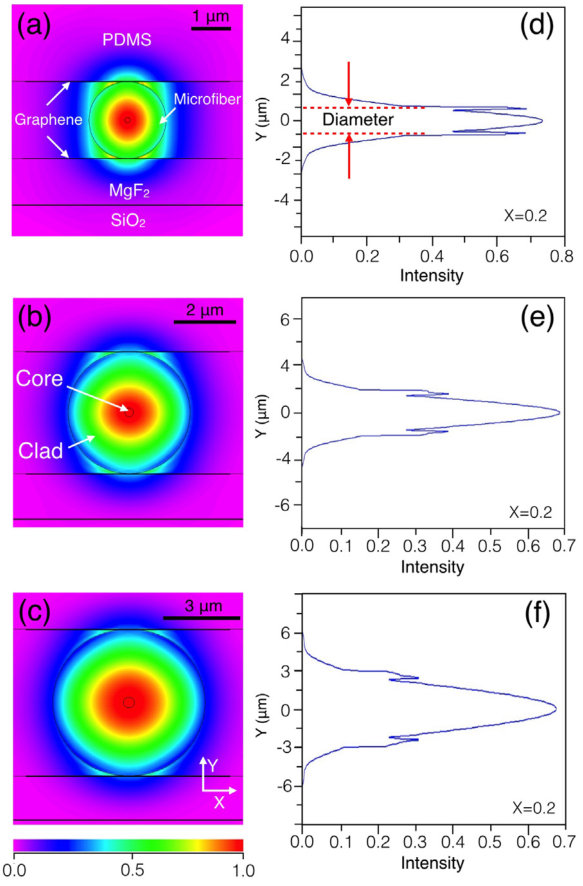

Fig. 1. Numerical simulation results. Light field distribution in the microfibre with (a) 2 μm (b) 4 μm and (c) 6 μm diameters, respectively. The intensity distribution of the DGCM in the microfibre with (d) 2 μm (e) 4 μm and (f) 6 μm diameters when X is fixed at 0.2. The maximum transmission intensity distribution of the microfibre is located at ($X=0$, $Y=0$).

The microfibre diameters (cladding) were assumed to be 2, 4 and 6 μm, corresponding to core diameters of 0.144, 0.288 and 0.432 μm. We first simulated the DGCM structure in the model. The microfibre is sandwiched in between two graphene sheets, where the top one is held by polydimethylsiloxane (PDMS, n = 1.406) film, and the bottom one is supported by a MgF_2 (n = 1.38) coated SiO_2 (n = 1.45) substrate. The light field distributions of the DGCM at different diameters are shown in Fig. 1 (a), (b) and (c), respectively. Fig. 1(d), (e), (f), depict the relationship between the Y-coordinate and the normalised intensity distributions at the selected fibre diameters when the X-axis is fixed at 0.2. The reason to simulate the mode field at $X=0.2$ is because the microfibre and graphene are in close contact in the original position (i.e., $X=0$), to show the distinct evanescent field distribution, thus we extract the values at the $X=0.2$ position. The intensities are 0.685, 0.39 and 0.313 corresponding to the 2 μm ($Y=\pm1$ μm), 4 μm ($Y=\pm2$ μm) and 6 μm ($Y=\pm3$ μm) microfibres. The results show that the microfibre with the smaller diameter can clearly improve the evanescent field and enhance the light–graphene interaction.

To obtain the GCM modulator, the microfibres were fabricated by stretching a standard telecommunication single-mode fibre under flame heating where the stretching distance was automatically controlled by computer programme. The microfibres with diameters from 2 to 6 μm were fabricated with a stretched length from ~1.2 to 2 cm. During the stretching process, the tapered length was inversely proportional [20] to the microfibre diameter. The monolayer graphene film in our experiment was synthesised on copper foil by chemical vapour deposition (CVD) [21]. Small-size free-standing graphene film (~0.2 × 0.5 cm^2 covered length along the light propagation direction) was obtained after etching the copper substrate with a 15% ferric chloride solution [22]. The graphene sheet could be reliably and firmly integrated into other structures because the atomically layered graphene layers are mechanically robust and can be naturally passivated on any surface. In our DGCM, we covered the microfibre with two planar graphene sheets in a parallel layout with the bottom graphene sheet transferred onto a MgF_2 coated silicon wafer to support the microfibre. The refractive index was selected as ~1.38 to reduce interface loss. To avoid damaging the device through the shrinkage stress of ultraviolet glue during drying, we used tape as a substitute to affix the microfibres. A polydimethylsiloxane (PDMS) membrane supporting the graphene sheet was coated on top of the microfibre to form a sandwiched structure in a van der Waals force combination. Compared with the DGCM, a piece of the free PDMS was coated on top of the microfibre in the SGCM, which ensured that the microfibre tightly fit the graphene film on the bottom.

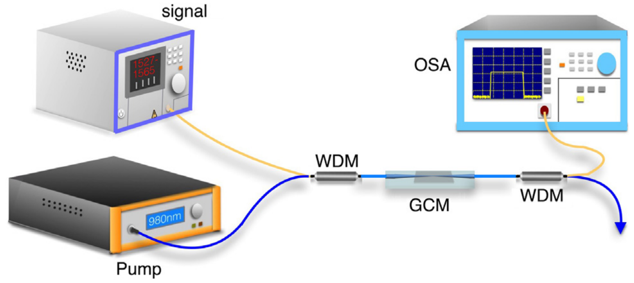

Fig. 2. Schematic of the all-optical intensity modulation experiment. Two 980/1550 nm WDMs were used to couple and split the pump and the light signal in the modulation process.

3. Experiment and discussion

A schematic setup of the optical intensity modulator is illustrated in Fig. 2. A 980 nm laser diode (LD) was employed as the pump laser and a broadband ASE light was used as the light signal. The lights were coupled to the GCM through a 980/1550 nm wavelength division multiplexer (WDM) for modulation. The output light of the GCM was incident to another 980/1550 nm WDM and split for measurement. The signal intensity was precisely monitored by optical spectrum analyser (OSA).

To explore the modulation effect of the GCMs, we measured the spectrum of the transmitted light signal at 0 mW to 600 mW pump powers. The intensity variation was analysed by comparing the corresponding values at a specific wavelength. Here, we selected 1550 nm for comparison. The intensity normalised output spectrum through the GCM is shown in Fig. 3(a). The transmitted intensity was enhanced significantly as the pump power increased from 0 mW to 600 mW. The transmittance of the signal intensity increased from −9.5 dBm to −7.4 dBm, from −9.9 dBm to −7.28 dBm and from −10.86 dBm to −6.61 dBm corresponding to the SGCM with 6 μm, 4 μm and 2 μm diameters, respectively. The detailed results are shown in Fig. 3(b). In contrast to the results from 1550 nm, the modulation depths are comparable to those from 1540 nm and 1560 nm, which confirm that the modulation is wavelength independent. Graphene's modulation was then investigated using double graphene sheet covered microfibres. The transmitted spectral intensity increased with the higher slope efficiency. Fig. 3(c) shows that the transmittance of the light signal increased from −10.2 dBm to −7.04 dBm, from −12.1 dBm to −7.22 dBm and from −13.5 dBm to −7.49 dBm, corresponding to the microfibres of 6 μm, 4 μm and 2 μm diameters. To verify that this modulation effect was caused by graphene, a contrast experiment was carried out by replacing the graphene film with free PDMS films on the same substrate. The measured slight transmittance variation of 0.24 dB was probably caused