Optics Communications 428 (2018) 77–83

Contents lists available at ScienceDirect

Optics Communications

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

Graphene-assisted all-optical tunable Mach–Zehnder interferometer based on microfiber

Zilong Liu, Yinghao Meng, Huifu Xiao, Lin Deng, Xiaonan Guo, Guipeng Liu, Yonghui Tian *, Jianhong Yang *

Institute of microelectronics and Key Laboratory for Magnetism and Magnetic Materials of MOE, School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, Gansu, China

ARTICLE INFO

Keywords:
All-optical devices
Fiber optics
Microstructure fiber
Modulation
Nanomaterials

ABSTRACT

We experimentally demonstrate a compact all-optical tunable Mach–Zehnder interferometer (MZI) based on microfiber. The graphene-assisted sandwich structure (GASS) integrated on the microfiber is adopted to form the all-optical tunable structure. The effective footprint of the fabricated device is about 7.31×8.66 mm^2 which is much more compact than other reported all-optical tunable MZIs based on fiber system. An out-fiber 1535 nm continuous-wave pump light is employed to irradiate the GASS vertically, which can produce the strong interaction of light-graphene. As a result, the device's response spectrum occurs red-shift due to the graphene's photothermal effect. Compared with the microfiber MZI with only the bottom graphene film, the tuning efficiency of the microfiber MZI with GASS is improved by 6 times, which is about 0.856 pm/mW. Meanwhile, the red-shift range can exceed one free spectral range (FSR) that means the resonant wavelength can be tuned to arbitrary wavelength in the range of the transparent window. This microfiber MZI with GASS featured with wavelength tunability, all-in-fiber, compact size, easy fabrication, and simple packaging is expected for the fabricated device to be used as all-optical modulator, tunable optical filter and optical switch, etc.

1. Introduction

Being a typical optical interference structure, Mach–Zehnder interferometer (MZI) has attracted considerable interest in the past few decades because of its simple structure and numerous applications in the field of optical and photonic devices [1], such as sensors [2–4], modulators [5–9], optical switches [10–13], filters [14,15], logical devices [16,17] and optical routers [18,19]. Generally, MZI can be fabricated based on a series of techniques such as integrated waveguide, fiber and microfiber [7,20,21]. MZIs fabricated with low-loss microfibers show the advantages in small footprints, easy fabrication and integration with fiber system due to the beneficial properties of microfiber such as tight optical confinement, strong evanescent fields and small mass/weight [21,22]. The first microfiber MZI assembled with two microfibers was demonstrated by Tong in 2008 [21]. However it cannot be tuned, which limits its applications in various occasions such as optical filter, optical switch, optical modulator etc.

All-optical tunable MZI is a vital element in signal processing and optical communication, including optical switch, optical filter and optical modulation. Specially, all-optical tunable microfiber MZI is more advisable for fiber systems due to its polarization insensitivity, compact size, low temperature coefficient, and simple packaging. The optical nonlinear effects generally including saturable absorption, stimulated Brillouin scattering, optical Kerr effect and stimulated Raman scattering were utilized in light-control-light devices [23–25]. Unfortunately, the relatively low nonlinear coefficient ($n_2 \approx 10^{-16}$ cm^2/W) of silica fiber will hinder the realization of the remarkable tuning efficiency. Meanwhile, a series of additional effects of the nonlinear modulation, such as the changes of extinction ratio and transmission loss, would restrict its future applications. In order to avoid these phenomena, thermo-optic effect can be used to achieve effective tunable device. Recently, graphene-assisted tunable devices have attracted widespread attention due to its outstanding thermal properties [25–27]. Combining with its remarkable properties, such as only an atomic-layer thick, excellent optical responses, 2.3% uniform absorbance, large mechanical deformation and outstanding environmental stability [28], graphene can flexibly and compatibly integrate with various substrates. Several techniques for transferring chemical vapor deposition (CVD) graphene onto planar substrates have been developed [29–31], which are proved to be still valid for transferring graphene films in millimeter-scale onto substrate-supported microfibers [32,33]. In the meantime, microfiber can offer

---

* Corresponding authors.
E-mail addresses: siphoton@lzu.edu.cn (Y. Tian), yangjh@lzu.edu.cn (J. Yang).

https://doi.org/10.1016/j.optcom.2018.07.036
Received 16 May 2018; Received in revised form 10 July 2018; Accepted 11 July 2018

high-intensity surface field and large evanescent field, enhancing the near-field interaction between the guided light and the surroundings. Therefore, various graphene microfiber integrated structures have been reported to realize enhanced light–matter interaction [34] and novel devices functions [35,36], including fiber lasers [37], switches [27], sensors [38,39] and all optical modulators [40–42].

In this paper, we employ graphene's ultra-wide absorption bandwidth and outstanding thermal properties to accomplish an efficient all-optical tunable microfiber MZI with graphene-assisted sandwich structure (GASS). To the best of our knowledge, this is the first demonstration of all-optical tunable microfiber MZI system based on all-microfibers. The proposed device consists of a graphene-sandwiched microfiber (GMF) and a microfiber. To realize all-optical tuning, an out-fiber pump light with the wavelength of 1535 nm is used to irradiate the GMF. By employing the direct interaction between the out-fiber pump light and graphene instead of the interaction between the evanescent field of in-fiber pump light and graphene, the graphene would generate Joule heating effectively and subsequently induces effective index change. The measured tuning efficiency is 0.857 pm/mW. Besides, the effective footprint of the fabricated device is about 7.31×8.66 mm^2 which is much more compact than other all-optical tunable MZIs based on the fiber system [20,27].

2. Fabrication

The proposed microfiber MZI with GASS consists of a GMF and a microfiber. To form a microfiber MZI, a tapered microfiber is fabricated by drawing a cleaned standard single-mode fiber (SMF-28, Corning Inc.) with the help of hydrogen flame and tapered drawing machine (Fig. 1(a)). The coating stripped standard SMF is finally drawn into bi-conical tapers with ~48 mm length for the tapered region and ~5.26 μm diameter for the uniform waist region (Fig. 2(a)). The transmission loss of the microfiber by this method is about 10^{-2} dB/mm [43]. For the convenience of manipulation, this microfiber is cut off and separated into two equal parts (Fig. 1(b)). And then the two parts are manipulated utilizing probes (Tungsten needle, 5 μm in diameter) to form a microfiber MZI with the help of electrostatic force and van der Waals force. The right part is vertically bent while the left part is stretched straight horizontally and coupled to the right part. During the manipulation, two red lasers are launched into the both single mode fibers for monitoring. Through carefully micromanipulation and the help of movable stage with a controllable stepper motor, two evanescent couplers between the two microfiber parts can be formed, which results in a microfiber MZI (Fig. 1(c)). The optical image of the microfiber MZI is shown in Fig. 2(b). The transmission loss and extinction ratio the microfiber MZI are −8.3 dB and 7.4 dB, respectively. Meanwhile, the graphene film fabricated by CVD is transferred to a substrate as the bottom graphene film after exfoliated from the copper foil (Fig. 1(d)). In order to enhance the robustness of the MZI for practical situations, Magnesium Fluoride (MgF$_2$) glass which has low refractive index of 1.38 is used as the substrate. The fabricated microfiber MZI is then placed on the MgF$_2$ glass substrate with bottom graphene film, one of the microfiber MZI's arms is placed on the graphene film region. The two couplers are fixed by low-index Teflon glue adhesive to further improve the mechanically robustness. Another graphene film is transferred to a commercial polydimethylsiloxane (PDMS) film (Gel-Pak Inc.) as the top graphene film by the same method. We choose PDMS because it has a low refractive index (1.406) and high optical transparentness. The PDMS film is covered above the whole microfiber MZI, meanwhile the top graphene film is aligned with the bottom graphene. The desired microfiber MZI with GASS is finally finished. As shown in Fig. 1(e), the sandwich structure, which composed of two pieces of graphene film, clamp the device tightly to ensure graphene and microfiber are in close contact. The PDMS film is applied to ensure the integrity of graphene and extend the service life (Fig. 1(f)). The effective footprint of the fabricated device is about 7.31×8.66 mm^2 and the length of the GASS region is measured as ~5.11 mm.

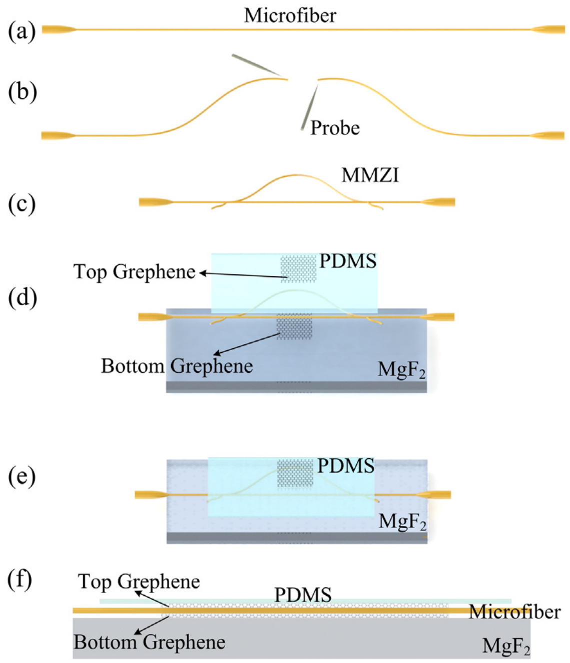

Fig. 1. (a)–(e) Fabrication processes of the microfiber MZI with GASS, and (f) lateral construction view of microfiber MZI with GASS.

Fig. 3 shows the measured Raman spectrum of a graphene film. The two most intense features are the G peak at ~1580 cm^{-1} and a peak at ~2700 cm^{-1}, historically named 2D, since they are two most prominent peaks always observed in graphene samples. From the intense of G peak and 2D peak, we can know that the graphene adopted to fabricate the propose device is mono-layer. The negligible D peak at 1350 cm^{-1} indicates low density of defects and high crystallinity of the graphene [44].

3. Characteristic of microfiber MZI

In order to assess the influence of graphene covered the microfiber, we numerically simulate the light-guiding in GMF using beam propagation method. In the simulation model, a microfiber with a diameter of 5.3 μm is sandwiched by two pieces of graphene film, and then put in the air. The graphene's refractive index is $2.52 + 2.24i$ at the wavelength of 1550 nm based on the intraband and interband conductivities [45]. The refractive indexes of microfiber and air at 1550 nm are 1.47 and 1, respectively. In Fig. 4(a), we plot the radial distributions of modes at wavelengths of 1550 nm in the GMF (black line) and the bare microfiber (red line), respectively. From the zoomed image we can see that, compared with the mode transmitting in the bare microfiber, the mode amplitude in GMF at the boundary decreases. The primary reason is that the light at the boundary can be absorbed by graphene due to the imaginary part of refractive index of graphene [25]. The upper inset shows the computed two-dimensional mode distribution of the GMF at 1550 nm. A near-field interaction between the graphene and microfiber happens owing to the existence of the evanescent field. Due to the relatively large diameter of microfiber [46] the near-field interaction between the graphene and microfiber is relatively weak. Compared with our previous work [25], mono-layer graphene and a relatively large diameter of microfiber (~5.3 μm) are used to realize interaction between graphene and microfiber. As we known, mono-layer graphene provides weaker nonlinear optical properties than N-layered graphene ($N \le 6$) as the thickness of thin flakes is significantly smaller than the wavelength of light [46]. It also provides weaker interaction with the evanescent field of microfiber than the multi-layer graphene [28]. Meanwhile,