Graphene-based plasmonic waveguides for photonic integrated circuits

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Abstract: We perform experimental investigations on the characteristics of graphene-based plasmonic waveguides for development of photonic integrated circuits. By embedding chemical vapor deposited graphene strip in a photoactive UV curable perfluorinated acrylate polymer with a low refractive index and material loss, the two-dimensional metal-like plasmonic waveguide demonstrated as a light signal guiding medium for high-speed optical data transmission. The fabricated graphene-based plasmonic waveguide supports the transverse-magnetic (TM) polarization modes with the averaged extinction ratio of 19 dB at a wavelength of 1.31 µm. The 2.5 Gbps optical signals were successfully transmitted via 6 mm-long graphene plasmonic waveguides. The proposed graphene-based plasmonic waveguides can be exploited further for development of next-generation photonic integrated circuit and devices.

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References and links

1. Introduction

Surface plasmon polaritons (SPPs), the coupling between collective excitations of free electrons in a metal and electromagnetic waves, are supported at the metal-dielectric interface. Since the SPPs can be confined within very small area beyond the diffraction limit, they are used as an information carrier for highly-integrated photonic circuits. Numerous plasmonic waveguide architectures have been investigated for development of on-chip nano-photonic devices [1]. On the other hand, the SPPs are also useful for long-range propagation-based applications. For an ultra thin metal strip embedded in homogeneous dielectric, the SPPs excited at the upper and lower metal-dielectric interfaces couple and form low-loss guided modes that are confined in the vertical and lateral direction [2]. Based on metal strip optical waveguide, numerous optical devices and telecom sub-systems have been demonstrated [2,3]. Although metal-based plasmonic waveguides offer potential for the development of novel optical devices, lack of the functionality of metal presents a drawback in explosive further applications.

Graphene, a monolayer of carbon atom bound in a hexagonal structure, has considered as an alternative candidate to comply with the metal-based plasmonic integrated systems because of its exceptional electric and photonic properties [4,5]. Compared to the conventional metal film, the functionality (e.g. conductivity) of graphene can be modified by means of chemical doping, electric filed, magnetic field, and/or gate bias voltage. Its high carrier mobility and zero bandgap characteristics allow us to develop novel photonic and optoelectronic devices such as solar cell, photodiode, modulator, and polarizer [5–8]. For further application of the graphene in photonic integrated circuits, guiding of light along graphene is essential. Numerous theoretical investigations have been performed on this issue [9–16]. When the imaginary part of the graphene’s complex conductivity is positive, a graphene layer behaves like a thin metal film that supports transverse-magnetic (TM) surface waves [9–11,16]. Although, an experimental result shows that a graphene polarizer can support TE-mode surface wave propagation [8], more elucidate experimental demonstration is highly necessary to support these theoretical investigations.

Here, we demonstrate experimentally that graphene-based plasmonic waveguides are served as a light signal guiding medium for optical signal transmission. We fabricated the chemical vapor deposited (CVD) graphene-based plasmonic waveguide in a photoactive UV curable perfluorinated acrylate polymer with a low refractive index and material loss. The characteristics of the guided modes depending on the polarization are investigated at a wavelength of 1.31 μm. A 2.5 Gbps optical signal transmission experiment was performed using the fabricated graphene plasmonic waveguide.

2. Experiment and discussion

Figure 1(a) shows the schematic view of the proposed graphene-based plasmonic waveguide studied in this study. The graphene strips are embedded in a homogenous dielectric medium. The dielectric consists of the under- and upper-cladding layers having the same refractive index. For fabrication, first, 20 μm-thick under-cladding material is spin-coated, and then cured with UV light. Graphene film grown by a thermal chemical vapor deposition (CVD)
method is transferred on the under-cladding layer. Graphene strips were defined by O₂ plasma ash process followed by a standard lithographic technique. Finally, the under-clad materials were spin-coated again forming the over-cladding layer. For dielectric layers, we used a commercial UV-curable polymer with the refractive index of 1.37, Exguide LFR from ChemOptics (www.chemoptics.co.kr). The propagation loss and the birefringence \((n_{\text{TE}} - n_{\text{TM}})\) of the optical polymer material at a wavelength of 1.31 \(\mu\)m are 0.06 dB/cm and 0.0003, respectively. The graphene films that are synthesized using 300 nm-thick Ni sputtered on SiO₂/Si substrates [17,18]. After etching the catalytic Ni films, the isolated graphene films were transferred to the under-cladding for device fabrication.

Figure 2 shows the Raman shift of the graphene that is transferred on the polymer surface. 2D peak and G peak indicating the presence of graphene are measured at ~2700 cm\(^{-1}\) and at ~1580 cm\(^{-1}\), respectively. The height of 2D peak is higher than G peak. This means that nearly single layer of graphene is transferred on the polymer surface. Similar to the CVD-grown graphene on Ni films, the transferred graphene film consists of various domains having 1 to ~12 layers of graphene and different size of up to 20 \(\mu\)m [18]. From the Raman shift measured from the transferred graphene, we confirmed that graphene film was successfully synthesized and transferred to the polymer dielectric.

Figure 1(b) exhibits the infrared images of the optical mode detected at the output of the fabricated graphene plasmonic waveguide, by using a charge-coupled device (CCD). The light from an optical source was scrambled to generate un-polarized light, and then coupled to the graphene plasmonic waveguide to excite the guided mode. A circularly symmetric spot is measured at the center of the graphene strip. The mode field diameter is 5 \(\mu\)m. The slab mode is attributed to the subtle refractive index difference between the under- and upper-cladding layers. The slight position shift of the input fiber in the vertical and lateral direction generates diminished the intensity of the light spot. However, the similar circularly symmetric spots are observed if the input fiber moves 250 \(\mu\)m in the lateral direction.

The CVD grown graphene may be considered as a quasi-two-dimensional electron gas system. Similar to a thin metal strip that transmits the surface-plasmon-polariton (SPP) mode [2], surface plasmons excited at the lower and upper graphene-dielectric interfaces couple and form a guided mode that is confined in the lateral and vertical directions. The two-dimensional mode confinement results in the formation of circular light spot. The guided modes of the graphene plasmonic waveguides are excited by means of a simple end-fire excitation using a single-mode polarization maintaining fiber (PMF).
Fig. 2. Raman shift of the fabricated graphene strip on the polymer surface. The inset depicts the optical images of the graphene strip.

To investigate the characteristics of the detected guided mode further, we measured the intensity change according to the polarization angle $\theta$. A polarizer is inserted between the waveguide output facet and the CCD. The infrared images are measured by the CCD according to the polarization angle. 90 degree corresponds to alignment of the electric field vector along the $y$-axis of the waveguide structure (see Fig. 1). As shown in Fig. 3(a), the effect of the polarization is clearly observed. At 90° polarization angle, the highest brightness of a circular spot is observed. As the polarization angle decreases, the output optical intensity of a circular spot decreases gradually. This indicates that TM polarization waves (electrical field is vertical) are guided mostly by the graphene strip embedded in a dielectric layer. However, tight confinement of the guided mode is observed for the polarization angle of 20°.

Figure 3(b) shows the normalized output power according to the polarization angle of the output beam. The output radiated light from the waveguide output facet was collected by a single-mode PMF. Then, the transmitted powers passing through the polarizer are measured with an optical power meter. As expected from the Fig. 3(a), the measured optical power of the waveguide is dramatic depending on the polarization. The transmitted optical power is maximum at 90° polarization and decreases gradually as the polarization angle decreases. The decrease is more dramatic if the polarization angle is lower than 50°. The propagation and coupling loss for TM-polarization are 2.1 dB/mm and 1 dB/facet, respectively. The inset of Fig. 3(b) exhibits the insertion loss of 5.7 mm-long graphene waveguides depending on the polarization. For TE-polarization, the insertion loss is about 19 dB higher than that of the TM-polarization. This extinction ratio includes the propagation and the coupling loss of the waveguide. The insertion loss of the channel 3 exhibits comparatively high insertion loss. It can be attributed to the high propagation loss due to imperfect uniformity of graphene film. Inhomogeneous and parasitic structures in a metal strip increase the propagation loss of the metal-based plasmonic waveguide [19,20]. Similar to this, discontinuity with gaps, ripples, wrinkles, and contaminants in the transferred graphene may contribute to the increment of the propagation loss, and consequently, the insertion loss of the graphene waveguide increases. We found more gaps and contaminants at the channel 3 graphene strip.

Compared to the characteristics of the metal-based strip optical waveguide [19–21], these of the guided mode in the graphene strip optical waveguides are comparatively high. This is attributed to high Ohmic loss of the CVD-grown graphene, as well as the graphene film qualities such as the continuity and uniformity of the graphene. The sheet resistance ($R_s$) of CVD-grown multilayer graphene is $770–1000 \, \Omega/$sq as measured by a four-point probe.
Because the SPPs are associated with the coupling between collective oscillation of free electrons in the metal and electromagnetic waves, the internal damping (Ohmic loss) of this excitation plays an important role in determining the propagation loss of the surface wave. Comparatively high resistance of graphene film induces rapid damping of the oscillation, and consequently, the propagation loss of the graphene-based plasmonic waveguide increases.

An improvement of the electrical properties of graphene film may result in the upgrade of the characteristics of the graphene waveguide. By using a chemical doping method, the graphene’s conductivity can be improved. Interface engineering that controls carrier type and density of graphene with polymethyl methacrylate or self-assembled monolayer (SAM) can improve the electrical properties of graphene [22]. The conductivity of graphene film can also be improved by increasing the charge (electron or hole) density of the graphene film. By varying the Fermi level by applying gate bias voltage to graphene, the charge density of graphene can be increased [4]. If an alternative electric field is applied in the normal direction to the graphene surface, a periodic control of the optical characteristics of the graphene waveguide is possible. On the other hand, the propagation loss of the graphene waveguide can be improved by increasing the field intensity that is confined into lossy graphene strip by introducing high-index dielectric slab layers above and below the waveguide strip [23].

To demonstrate the ability of the graphene plasmonic waveguide to transmit optical data, we performed the transmission experiment of 2.5 Gbps optical signals, referring to the previous study [3,21]. An electrical signal from a pulse pattern generator (PPG) is transmitted to an optical transmitter (Tx) module. A modulated TM-polarization optical signal from the Tx module is transmitted to the input facet of the graphene waveguide through the PMF, and excites the guided mode via a direct end-fire coupling. Subsequently, the wave propagates along the graphene strip, and then the beam reaches a photodiode in the optical receiver (Rx) module. The electrical signal from the PD in the Rx module is magnified by the receiver IC.
consisting of a TIA and a limiting amp. Finally, the electrical signal is investigated with a digital communication analyzer (DCA).

Figure 4(a) shows the assembled high-speed optical signal transmission experiment set-up with the 5.7 mm-long graphene strip optical waveguide. The input and the output facets of the graphene waveguide are coupled with the PMF and the photodiode, respectively. The measured eye diagram of the 2.5 Gbps optical signal is shown in Fig. 4(b). A 2.5 Gbps non-return-to-zero pseudorandom bit sequence (2^{31}-1) of the optical signals was transmitted through the graphene plasmonic waveguide. The eye diagram was clearly open at room temperature. The measured eye diagram is nearly identical with the eye pattern of the original back-to-back signal (the inset of Fig. 4(b)). The root mean square time jitter of the transmitted signal was less than 10 ps from the original signals, which means that the pulse broadening by the waveguide dispersion is negligible, as we expected. The bit error rate (BER) obtained under the best condition was estimated to $10^{-10}$. From the clearly opened eye diagram, we confirmed that the graphene plasmonic waveguide transmits high-speed digital signals up to 2.5 Gbps without any pulse distortion.

3. Conclusion

We investigated the characteristics of the graphene-based plasmonic waveguide for optical signal transmission. The graphene strips embedded in a dielectric are served as a high-frequency optical signal guiding medium. For 6 mm-long graphene waveguide, the TM polarization wave is transmitted with the averaged extinction ratio of 19 dB at the telecom wavelength of 1.31 μm. 2.5 Gbps data transmission was successfully accomplished with the graphene waveguide. Based on these experimental results, we concluded that the graphene plasmonic waveguide may be modeled as the ultra thin metal-like waveguide. The graphene-based plasmonic waveguide can be exploited further for development of next-generation integrated photonic circuits on a chip.

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