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Abstract: A dynamically tunable electromagnetically induced transparency (EIT) system consisting of two coupled micro-ring resonators, one of which is embedded with a graphene layer, is proposed and numerically demonstrated. The effective refractive index of the graphene-based micro-ring resonator can be significantly tuned by varying the gate voltage applied on graphene, inducing significant modulation of the resonant wavelength of EIT transparency window over a wide spectral bandwidth. Typical tunability of the EIT resonance is approximately 1.62 nm/V around 1550 nm, which is much better than that based on a nanoelectromechanical EIT system. Such a configuration implies the possibility of constructing various optical devices toward realization of photon pulse trapping, optical modulation, and filtering on a chip.

Index Terms: Coupled resonators, electromagnetically induced transparency (EIT), integrated optics, resonance.

1. Introduction
The electromagnetically induced transparency (EIT) effect, which is a spectrally narrow optical transmission window within a broad absorption spectrum, originates from the quantum interference of multiple excitation pathways through short and long-lived resonances [1]. The EIT effect in the atomic medium is formed by the coupling between different Zeeman levels [2]–[6]. Within this spectral window, it is accompanied by dramatically slowed photons and enhanced nonlinearities, which offers the capability to manipulate light at a few-photon power level [7]. However, a significant limitation to the use of the EIT effect is the limited material choices and stringent requirements for the coherence of excitation pathways in atomic systems. In recent years, various optical structures have been proposed to realize EIT-like phenomena in optical systems, promising great potential applications in optical routers, buffer memories, and optical signal processing. Typical examples include coupled resonators [8], [9], metamaterials [10]–[13], photonic crystals [14], a hybrid system...
with dielectric waveguides and subwavelength gratings [15], [16], plasmonic resonator antennas coupled with a dielectric waveguide [17], and plasmonic resonator systems [18]. Generally, most of these configurations can only enable light transparency at a fixed operating wavelength once the systems are fabricated, which will significantly limit practical applications. To implement actively controllable EIT-like resonance, several schemes have been proposed by using nonlinear materials [19], thermal tuning materials [20], [21], and nanoelectromechanical systems [22].

As one of the key components on silicon-on-insulator (SOI) platform, micro-ring resonators have been intensively investigated and demonstrated to enable construction of various optical devices, such as filters [23], polarization rotators [24], photonic logic gates [25], modulators [26], and sensors [27]. By utilization of two coupled micro-ring resonators, an EIT-like effect has been demonstrated and widely investigated due to their easy operation, engineering transparency window, and easy integration on a chip [8], [28], [29]. Recent research on the EIT effect has moved towards constructing various coupled micro-ring resonators that have the capability of operating with a dynamically tunable EIT transparency window via thermal, nonlinear, and carrier tuning [29]–[31].

Graphene, a single sheet of carbon atoms arranged in a two-dimensional honeycomb lattice, shows great promise for developing highly efficient optoelectronics devices due to its outstanding electrical and optical properties [32], [33]. Graphene is unique because its conductivity can be dynamically tuned by modulating the chemical potential via varying gate voltage or chemical doping [33]. Graphene is emerging as an attractive material for the development of high-performance optical devices, such as modulators, photodetectors, and polarizers [34]–[37]. Meanwhile, the unique characteristics of graphene have been intensively introduced to develop tunable micro-ring resonators [38], [39] and demonstrate actively controllable EIT-like effects [40]–[42]. By taking advantage of differences in attenuation for the TM and TE modes when graphene is involved in a dielectric waveguide, we have previously proposed and demonstrated a silicon waveguide polarizer as well as a polarization beam splitter on SOI platform [37], [43]. However, to the best of our knowledge, little work has been devoted to exploring the utilization of graphene to construct coupled micro-ring resonators for controllable EIT transparency window on SOI platform. In this article, we propose an EIT-like system comprised of two coupled ring resonators, one of which is embedded with a sheet of graphene. Similar to the tunable EIT system in atomic-like medium where the EIT window can be opened or closed by controlling the coupling field [2], here the present results show that EIT-like transparency window is flexibly tuned by slightly adjusting the gate voltage applied on graphene. The designed EIT micro-ring resonator presents much larger tunability, even in comparison with that based on a nanoelectromechanical system [22].

2. Tunable Micro-ring Resonator With Monolayer Graphene Embedded

Consider a graphene-based tunable micro-ring resonator, shown in Fig. 1, which consists of a graphene-based micro-ring resonator and a bus waveguide, spaced with a gap $d$ between them. The bus waveguide [see Fig. 1(c)] is a conventional silicon rib waveguide with a thin, centrally located hexagonal boron nitride (hBN) layer ($t_2 = 7$ nm) sandwiched between an upper and lower silicon layer. The micro-ring resonator [see Fig. 1(b)] has the same cross-section as the bus waveguide except that a monolayer graphene is embedded in the central region of the hBN layer. For the micro-ring resonator, a capacitor is formed as graphene/hBN/doped silicon configuration. Here the hBN layer is introduced to act as an insulator that allows graphene to maintain its high mobility because it is atomically flat and free of dangling bonds and charge traps [44]. The doped silicon layer is connected with one metallic electrode, and the graphene layer is extended to connected the other metallic electrode. In this case, an applied voltage, as shown in Fig. 1 may tune the carrier density of graphene in real-time, and hence the chemical potential of graphene can be flexibly changed [32], [35], [45]. The relationship between the chemical potential and gate voltage will be discussed later in this section. It should be noted here, the influence of a metal electrode on the modal field distributions of the dielectric waveguide can be effectively avoided by keeping a large distance between the metal electrode and micro-ring resonator in a practical situation. However, to prevent the graphene layer from dropping down and touching the doped silicon, the
Fig. 1. (a) Schematic of a tunable micro-ring resonator with a sheet of graphene embedded. (b) Cross-sections for the micro-ring resonator with a sheet of graphene embedded (left panel) and the bus waveguide (right panel) in the regions bounded by the dashed lines in (a). The relative permittivity of hBN layer is 3.92.

distance between them should be properly selected. For future experimental implementation of the micro-ring resonator, first, we can prepare six shadow masks for the doped silicon substrate, two half micro-ring resonators, bus waveguide, and two metal electrodes. By properly arranging the order of the six masks, choosing the deposition methods, and transferring the graphene layers from the copper foil, the presented micro-ring resonator might be fabricated. It’s well-known that the resonant wavelength of a micro-ring resonator is determined by the effective mode index of the resonator once its structural parameters are fixed. In the present scheme, it is highly anticipated that the resonant wavelength of the graphene-based micro-ring resonator can be modulated by varying the effective mode index via tuning the gate voltage.

The optical response of graphene is characterized by its surface conductivity, $\sigma_g$, which can be retrieved by the Kubo formula [32]

$$\sigma_g = i \frac{e^2 k_B T}{\pi \hbar^2 (\omega + i \tau^{-1})} \left[ \frac{\mu_c}{k_B T} + 2 \ln \left( \exp \left( -\frac{\mu_c}{k_B T} \right) + 1 \right) \right]$$

$$+ i \frac{e^2}{4\pi \hbar} \ln \left[ \frac{2 |\mu_c| - \hbar (\omega + i \tau^{-1})}{2 |\mu_c| + \hbar (\omega + i \tau^{-1})} \right]$$

(1)

where $k_B$ is the Boltzmann constant, $\hbar$ is the reduced Planck constant, $\lambda$ is the wavelength (angular frequency $\omega$), $T$ is temperature, $\mu_c$ is the chemical potential, and $\tau$ is the momentum relaxation, respectively. In this work, we have chosen $T = 300$ K, and $\tau = 0.5$ ps for the calculation. It is apparent that graphene’s surface conductivity is closely related to the chemical potential. Originating from the fact that carbon atoms of graphene merely distribute periodically in the horizontal plane, a sheet of graphene is commonly regarded as highly anisotropic material, i.e., the in-plane permittivity ($\varepsilon_{||}$) can be tuned by the chemical potential, whereas the out-of-plane permittivity ($\varepsilon_{\perp}$) is kept constant at 2.5 [46]. By treating the graphene monolayer as an ultra-thin film, $\varepsilon_{||}$ can be written as [33]

$$\varepsilon_{||} = 1 + \frac{i \sigma_g k_0}{k_0 \Delta}$$

(2)
where $\Delta$ is the physical thickness of graphene ($=0.34$ nm), $\eta_0$ is the impedance of air ($\approx 377 \Omega$), and $k_0$ is the wavenumber ($=2\pi/\lambda$) in vacuum. The surface conductivity $\sigma_g$ and in-plane permittivity $\varepsilon_{||}$ of graphene as a function of chemical potential $\mu_c$ at 1550 nm are shown in Fig. 2. It can be seen that $\sigma_g$ varies sharply around $\mu_c = 0.4$ eV, leading to a significant change for $\varepsilon_{||}$ accordingly. For a scheme shown in Fig. 1, the chemical potential of graphene can be determined by the gate voltage applied on the graphene layer [35]

$$\mu_c = \hbar V_F \sqrt[\pi] { \frac { \varepsilon_0 \varepsilon_H } { d_H } } |V_g - V_{Dirac}|$$

where $V_F = 10^6$ m/s is the Fermi velocity, $\varepsilon_0$ is the permittivity of the vacuum, $\varepsilon_H$ is the relative permittivity of hBN, and $d_H = t_2/2$ is the thickness of the insulator (hBN) between the graphene monolayer and doped silicon layer. $|V_g - V_{Dirac}|$ can also be seen as the applied gate voltage $V_g$ since $V_{Dirac}$ is closed to zero [see Fig. 1].

Considering that a sheet of graphene is inserted into a dielectric waveguide, the dominant electric field, $E_y$, of the TM mode is much unaffected since a sheet of graphene is ultra-thin and its out-of-plane permittivity ($\varepsilon_{\perp}$) is kept constant at 2.5. Meanwhile, the field intensity, $E_z$, of TM mode is extremely weak since graphene is located in the center of the dielectric waveguide in our case [47], [48], hence the influence of embedded graphene on the modal field distribution of the TM mode could be negligible. As for the TE mode, both the field intensity of $E_x$ and $E_z$ are significant and parallel to the graphene sheet. Consequently, the TE mode will feel the variation of $\varepsilon_{||}$ significantly. Then, with a monolayer graphene involved in the micro-ring resonator [shown in Fig. 1], it is supposed to have a much larger influence on the modal characteristics of the TE mode than on those of the TM mode. In other words, for the purpose of achieving the largest tunability of the resonant wavelength, the TE mode should be selected for the design of the micro-ring resonator. Fig. 3 clearly indicates that the effective refractive index of the TE mode [Real($n_{eff}$)] undergoes very significant changes around $\mu_c = 0.4$ eV. It is monotonically reduced from 2.119 to 2.102 when $\mu_c$ undergoes a change from 0.4 to 0.8 eV. In addition to having a large effective mode-index tunability, the loss coefficient, represented by the imaginary part of the effective mode index [Imag($n_{eff}$)], is kept at very low levels if $\mu_c > 0.4$ eV. To summarize, a sheet of graphene is highly expected to enable large resonant wavelength tunability as well as high transmission for the micro-ring resonator.

The transmission spectrum of the graphene-based micro-ring resonator as a function of light wavelength for different $\mu_c$ is shown in Fig. 4(a). It is clearly seen that the resonant wavelength is strongly dependent on $\mu_c$. The resonant wavelength shifts from 1550.45 to 1549.6 nm with $\mu_c$ varying from 0.42 to 0.45 eV, corresponding to a gate voltage change from 2.085 to 2.394 V. We have noted in a recent study on an optical modulator consisting of a graphene/graphene capacitor integrated along a ring resonator that the resonant wavelength can be significantly tuned over a wide range of gate voltage applied on graphene [49]. The numerical result agrees with the experimental result very well. It should be noted that, in our case the resonant wavelength can be varied within a much larger range if a wider range of $\mu_c$ is used. In addition, it can be highly anticipated to effectively enlarge the adjusting range of the effective mode index by embedding more graphene layers into
3. Tunable Electromagnetically Induced Transparency in Graphene-Based Coupled Micro-ring Resonators

The EIT-like effect in coupled micro-ring resonators is resulting from the destructive interference between the bright and dark resonators [9], [28], [29]. Generally, the bright and dark resonators...
Fig. 5. Schematic of the proposed graphene-based coupled micro-ring resonators. The gap between the small micro-ring resonator and the bus waveguide is $d_1$, and the gap between the two micro-ring resonators is $d_2$.

Fig. 6. (a) Transmission spectrum of the tunable graphene-based micro-ring resonators. (b) Peak wavelength of EIT transparency window versus $\mu_c$ and $V_g$. (c)–(e) Distributions of the electric field $|E|$ corresponding to (c), (d) the two transmission dips, and (e) the transmission peak with $\mu_c = 0.42$ eV. In the simulation, the geometrical parameters are chosen as $d_1 = 150$ nm, $d_2 = 150$ nm, and $R_1 = 5 \mu$m, while the other parameters are the same as those in Fig. 4.

have the same resonant wavelength, around which the bright mode can be excited by coupling with the bus waveguide directly, while the dark resonator is not allowed to directly interact with the bus waveguide but can be excited through the near-field coupling with the bright resonator. With proper design of the structural parameters, the bright resonator usually possesses a low quality factor (Q), whereas the dark resonator has a high Q. The schematic illustration of the tunable graphene-based coupled micro-ring resonator is shown in Fig. 5. The small micro-ring resonator is directly coupled with the bus waveguide, acting as the bright resonator, while the large one with a sheet of graphene involved does not interact with the bus waveguide directly, serving as the dark resonator. Consequently, the destructive interference between the two micro-ring resonators leads
to the EIT effect. Choosing a bending radius $5 \mu \text{m}$ for the small micro-ring resonator, the resonant wavelength (1549.6 nm) almost coincides with that of the graphene-based one, and the Q value is kept at a relatively low level (smaller than that associated with graphene).

The peak wavelength of the transparency window is primarily determined by the resonant wavelength of the dark resonator [53], [54]. By varying $\mu_c$ to tune the resonant wavelength of the dark resonator, we are able to dynamically tune the EIT transparency window. Fig. 6(a) shows the simulated transmission spectrum with $\mu_c$ changing from 0.42 to 0.45 eV with a step of 0.01 eV. A pronounced EIT-like transmission is clearly observed for each chemical potential. Here, it is worth noting that the EIT peak has a very high transmission (>90%) due to the low absorption loss from graphene when $\mu_c > 0.4$ eV. More interestingly, the peak wavelength of EIT-like transmission can be dynamically tuned by altering $\mu_c$ to shift to a shorter wavelength while increasing $\mu_c$ [see Fig. 6(b)]. As the wavelength is tuned to the dips in transmission [see Fig. 6(c) and (d)], very weak light intensity is observed in the output port. However, by tuning the wavelength to make the micro-ring resonator work at the transparency window, light can be transmitted through the output port almost entirely [see Fig. 6(e)]. With $\mu_c$ tuned from 0.42 to 0.45 eV, (associated with the gate voltage from 2.085 to 2.394 V) the peak wavelength of the EIT resonance shifts from 1550.25 to 1549.75 nm [see Fig. 6(b)]. The tunability of the EIT resonance is approximately 1.62 nm/V, which is significantly larger than that based on a nanoelectromechanical system with a tunability of 0.06 nm/V [22].

4. Conclusion

In summary, we have proposed a tunable EIT-like system consisting of two coupled micro-ring resonators, one of which is embedded with a monolayer graphene sheet. The simulation results show that the resonant wavelength of the EIT transparency window can be flexibly tuned by varying the gate voltage applied on graphene. The estimated tunability of the EIT resonance is approximately 1.62 nm/V, which is significantly larger than that based on a nanoelectromechanical system with a tunability of 0.06 nm/V [22]. Additionally, the EIT peak can be kept with a very high transmission due to the low absorption loss from graphene. It should be noted that such a configuration offers the extra dimension of the effective refractive index tunability of the micro-ring resonator by tuning the chemical potential via varying the gate voltage, which enables the designed EIT system to operate with variable output power. Finally, under the tunability of graphene’s chemical potential, it can be highly expected that the coupled micro-ring resonators have less wavelength dependence and larger fabrication tolerance as opposed to those associated with previous EIT systems [8], [28]–[31].

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References


