OSA Advanced Photonics Congress (AP) 2020 (IPR, NP, NOMA, Networks, PVLED, PSC, SPPCom, SOF)
OSA Technical Digest (Optica Publishing Group, 2020), paper NpW1E.2
https://doi.org/10.1364/NP.2020.NpW1E.2

Nonreciprocal Silicon Photonic Coupler Exploiting Graphene Saturable Absorption

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Abstract: We present a broadband half-duplex high-power photonic isolator using the exceptional point in a non-Hermitian nonlinear silicon slot coupler. The concept relies on spatially asymmetric saturable losses, by overlaying one waveguide with graphene.

1. Introduction

Components with nonreciprocal response are highly desirable in integrated photonics. Diodes exhibit nonreciprocal transmission and are the building blocks of more complex components such as isolators and logic gates; these components are of fundamental importance in devices with higher levels of functionality such as sources and all-optical processing units. Presently, magnetic materials exhibiting Faraday rotation are mostly used for optical isolators, but are costly to hybridly integrate in photonic platforms. Consequently, alternative ways have been proposed to break Lorentz reciprocity, such as the combination of nonlinearity and spatial asymmetry. This concept has been mainly explored using the Kerr effect in photonic resonators.

In this work, we present a concept broadband photonic diode relying on graphene saturable absorption (SA) in an asymmetric coupler. In the near infrared and for a chemical potential (μ_c) below the half photon energy, graphene's absorption is predominately due to interband transitions. This absorption is broadband and saturable with a sub-ps response time and presents a much lower power threshold compared to the Kerr effect. Our concept is based on exceptional points (EPs) [1], singularities in the eigenvalue space of non-Hermitian systems. In our approach, the EP in a lossy waveguide coupler combined with the asymmetric field overlap with the nonlinear SA material gives rise to nonreciprocal functionality, manifested as uni-directional transmission.

2. Concept, analysis and design

We consider the abstract waveguide coupler depicted in Fig. 1(a), consisting of one lossless waveguide (blue) and one nonlinear lossy waveguide (orange), whose losses are assumed fully saturable. The waveguides are otherwise identical, i.e., modes have the same propagation constant (real part). The coupler is configured as a two-port component with ports 1 and 2 denoting opposite ends of the lossy and lossless waveguides, respectively.

Assuming that the coupler's length is equal to the coupling length $L \approx L_c = \pi/2|\kappa|$, κ being the coupling coefficient, and $\alpha/2|\kappa| \gg 1$ then for low power input the device operates above the EP: Guided power in the lossless waveguide is weakly coupled to the lossy one, while power in the lossy waveguide is greatly attenuated before being weakly coupled to the lossless waveguide [2]. For the port configuration in Fig. 1(a) this translates to very low reciprocal transmission. For high power excitation from the lossy waveguide (port 1), losses are saturated ($\alpha/2|\kappa| \ll 1$) allowing full coupling to the opposite waveguide. Thus, transmission to port 2 is high (through direction). On the contrary, excitation of the lossless waveguide does not sufficiently overlap with the SA material and coupling is suppressed due to the EP, leading to low transmission to port 1 (isolated direction).

A coupled mode framework is used for the qualitative analysis and design of the device. Assuming that z is the propagation direction, $A_{1,2}$ the E-field complex amplitude on the top/bottom waveguide normalized by the saturation amplitude ($|A_{\text{sat}}|$), β the real phase constant for both waveguides, and α the low-power attenuation coefficient for the lossy waveguide, then the system describing the device is

$$\frac{\partial}{\partial z}\begin{bmatrix}A_1\\A_2\end{bmatrix} = \begin{bmatrix}-j\beta - \dfrac{\alpha}{1+|A_1|^2} & \kappa \\ -\kappa^* & -j\beta\end{bmatrix}\begin{bmatrix}A_1\\A_2\end{bmatrix}. \tag{1}$$

Solving Eq. (1) leads to the transmission coefficients in both directions, the forward T_{21} and backward T_{12}. Note that we assume excitation of only one port at any time. In the linear regime, the EP is located at $\alpha/2|\kappa| = 1$. In the nonlinear regime, the state of the system is power dependent, i.e., high power signals alter the state relative

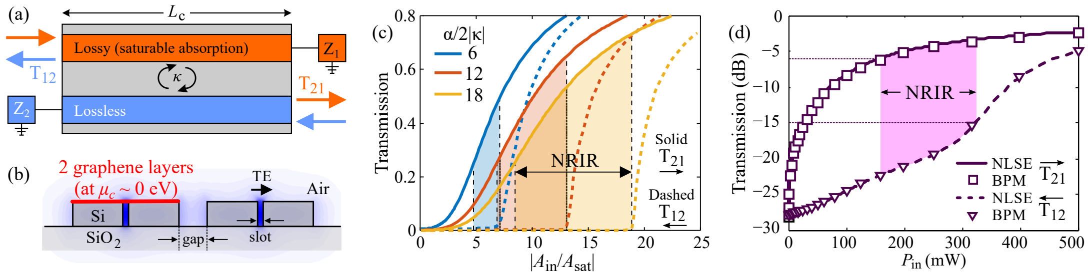

Fig. 1. (a) Abstract two-port nonlinear asymmetric waveguide coupler of length $L = L_c = \pi/2|\kappa|$; terminals $Z_{1,2}$ denote matched loads. (b) Proposed physical cross section (not to scale) of the silicon slot coupler with the symmetric supermode; the arrow indicates the dominant mode polarization. (c) Forward (T_{21}) and backward (T_{12}) transmission vs. normalized input amplitude using CMT; colors correspond to different values of the loss parameter $\alpha/2|\kappa|$. (d) Forward (solid) and backward (dashed) transmission for the graphene waveguide coupler with SA shown in (b), using coupled NLSE and BPM.

to the EP, which drastically changes the response. The transmission coefficients for $\alpha/2|\kappa| = 6, 12$ and 18 vs. the normalized input field amplitude are presented in Fig. 1(c), where the shaded regions corresponds to $T_{21} \geq -6$ dB and $T_{12} \leq -15$ dB; this is the Non-Reciprocal Intensity Range (NRIR) of this device [3]. Note that low power signals are heavily attenuated in both directions and also there exists a limiting power threshold beyond which isolation abruptly drops (T_{12} rises). The latter happens when even the low fraction of power coupled from the lossless to the lossy waveguide is able to sufficiently saturate losses to restore normal coupling operation.

The physical implementation of the coupler is shown in Fig. 1(b). Each Si-slot waveguide consists of two identical ribs, 360 nm wide and 180 nm tall, forming a 40 nm slot, while the gap is 640 nm leading to $L_c = 800\ \mu$m. On the top face of the left waveguide two uncoupled graphene layers are deposited, which are assumed to be unbiased ($\mu_c = 0$ eV) and possess a saturation intensity of $I_{sat} = 1$ MW/cm^2. The two layers have a total surface conductivity of 121.7 μS, leading to 0.42 dB/μm linear losses, assumed fully saturable.

For validation, we firstly derive a pair of nonlinear Schrödinger equations (NLSE) [4], for the TE mode of each isolated waveguide, heuristically coupled by the weak coefficient κ. The SA loss coefficient of the graphene-overlaid waveguide is formally introduced by using the overlap of the mode distribution with graphene. The simulation results are shown in Fig. 1(d). Although there are moderate forward losses (6 to 3 dB), the threshold CW power is reasonably low (160 to 320 mW), which showcases graphene's low saturation intensity. Note that the bandwidth limiting factor is the wavelength dispersion of the coupling coefficient and mode profile, both of which are low. The results were validated by full-vector 3D beam propagation method (BPM) simulations, depicted with markers in Fig. 1(d); the custom BPM was implemented with finite elements in the cross-section and wide-angle Crank-Nicolson scheme in the propagation direction, iteratively stabilized for nonlinearity.

3. Conclusions

Our analysis shows that coupled graphene-overlaid waveguides can operated as nonlinear optical diodes, compatible with standard photonic integrated circuit technology. Our approach towards nonreciprocity provides an alternative route to the more commonly used Kerr effect, thanks to graphene's SA ultra fast response and low saturation intensity. Finally, our concept has a general scope and demonstrates how SA in conjunction with EPs can be exploited to design nonreciprocal integrated photonic components.

Acknowledgment

Co-financed by Greece and the European Union (European Social Fund) through the Operational Programme "Human Resources Development, Education and Lifelong Learning 2014-2020" in the context of project "Design of nonlinear silicon devices incorporating graphene and using the Parity-Time symmetry concept" (MIS 5047874).

References

1. M.-A. Miri and A. Alù, "Exceptional points in optics and photonics," Science **363** (2019).
2. D. Chatzidimitriou and E. E. Kriezis, "Optical switching through graphene-induced exceptional points," J. Opt. Soc. Am. B **35**, 1525–1535 (2018).
3. D. L. Sounas and A. Alù, "Fundamental bounds on the operation of fano nonlinear isolators," Phys. Rev. B **97** (2018).
4. D. Chatzidimitriou, A. Pitilakis, and E. E. Kriezis, "Rigorous calculation of nonlinear parameters in graphene-comprising waveguides," J. Appl. Phys. **118**, 023105 (2015).