Graphene-based solitons for spatial division multiplexed switching

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Spatial division multiplexing utilizes the directionality of the light's propagating \( k \)-vector to separate it into distinct spatial directions. Here, we show that the anisotropy of orthogonal spatial solitons propagating in a single graphene monolayer results in phase-based multiplexing. We use the self-confinement properties of spatial solitons to increase the usable density of states (DOS) of this switching system. Furthermore, we show that crossing two orthogonal solitons exhibits a low (0.035 dB) mutual disturbance from another enabling independent \( k \)-vector switching. The efficient utilization of the DOS and multiplexing in real space enables data processing parallelism with applications in optical networking and computing.

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In contrast to light in linear media, highly nonlinear media are able to modify the index of refraction of an electromagnetic wave along its own path, enabling the formation of spatial solitons [1]. A spatial soliton changes the index of the material just enough to balance spatial dispersion, propagating with an unchanging mode profile. This spatial stability enables light redirection and routing applications [2–4]. Moreover, nonlinear field interactions of solitons with photons give rise to all-optical switching and beam-steering applications [5]. While a steered output of a single signal is useful for many applications, performance in computing and data processing strongly depends on the switching density of multiple signals. Here, we show phase-based beam steering of spatial solitons and demonstrate independent beam control of two pairs of crossing in-plane spatial solitons. Such independence of two orthogonal pairs of all-optical switches enables application toward all-optical computing.

Photonic waveguides are the basis for monolithic integrated photonic devices [6–9]. The shape and area of the waveguide cross section define the modes that are able to propagate in the waveguide, and the cross section of the waveguide is a directionally dependent property of the waveguide [10–12]. When waveguides cross each other orthogonally, some amount of light from one waveguide will cross-couple to the other [13]. Such crosstalk is due to the nature of the modes traveling within the orthogonal waveguides; at the waveguide crossing, neither waveguide can support its primary mode. Thus, the electromagnetic wave experiences an impedance mismatch between the regions of the intersection versus the waveguide portion. At this junction, light begins to diffract from the intersection.

Here, EM fields are lost due to scattering, diffraction, and modal mismatches which, taken together, typically reduce the amount of light transferred across the waveguide intersection by 0.16 dB in silicon photonics [13]. In cases where the waveguides support primary modes of differing wavelengths, the respective insertion loss of each waveguide increases, since only certain spectral regions can be optimized for cross-coupling due to dispersion.

The mathematical basis of this problem lies in the isotropicity of the refractive index of the two crossing waveguides. Due to the isotropic nature of the index, the two directions of propagation cannot be separated. In an anisotropic medium, this is not the case. Here, each direction of the electric field can experience a different index, and two beams propagating with distinct directions will not necessarily experience the same index profile. Spatial solitons must be anisotropic due to the field vector dependence of the nonlinear media creating them. This gives rise to the unique ability to cross each other orthogonally which can be realized with solitons, as discussed here, leading to little mutual interaction useful to maximize switching density.

Solitons occur in nonlinear physical systems, including nonlinear optical systems, and can be classified as temporal or spatial. Optical solitons have been investigated for many applications in both communications and computing [5,14–19]. Temporal solitons increase the DOS relative to linear systems by holding the pulses of light together in time, while the spatial solitons increase the DOS relative to linear systems by acting as its own waveguide, holding light together in space. In this sense, the spatial soliton maintains a constant width, i.e., beam divergence, while the temporal soliton maintains a constant pulse shape, i.e., temporal dispersion. For Kerr nonlinear media, such as graphene [20,21], in which the refractive index is a function of intensity, secant spatial solitons are given by the nonlinear Schrödinger (NLS) equation [22]:

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where $u$ is the envelope of the electric field with a solution Eq. (2) that describes the optical spatial solitons propagating in a two-dimensional plane with a secant intensity profile [23]:

$$E(x, z) = \frac{1}{k_0 a_0} \sqrt{\frac{n_0}{n_2}} \exp \left( \frac{iz}{2k_0 a_0} \right) \sech \left( x - x_0 \right),$$

(2)

where $k$ is the wavevector; $n_0$ and $n_2$ are the indices of the nonlinear material independent of field strength and dependent on field strength respectively, $n = n_0 + n_2 E^2$. Graphene is a Kerr-type nonlinear optical material with an index of refraction that increases with beam intensity originating from its linear gapless energy dispersion of charge carriers that relates to each other in graphene have minimal interaction with anisotropic media, such as graphene is anisotropic, even when the linear refractive index of the material is isotropic. This results in the index of refraction for the electric field, it follows that the index of refraction for a wave with the electric field propagating inside a Kerr-type media, such as graphene is anisotropic, even when the linear refractive index of the material is isotropic. This results in an anisotropically graduated index of refraction that varies proportionally with intensity in the direction of electric field [26]:

$$n = n_0 + n_2 I = n_0 + \frac{3}{2n_0^2 \varepsilon_0 c} \chi^{(3)} \frac{1}{2} n_0 \varepsilon_0 c |E_x|^2.$$  

(3)

Then, for graphene, $n \cong 3 + 5.225 \times 10^{-16} |E_x|^2$. From this, we see that two optical spatial solitons crossing orthogonally to each other in graphene have minimal interaction with another; each with orthogonally directed electric fields will independently affect orthogonally directed changes to the index of refraction. This independence increases the DOS.

Based on these arguments, we are interested in investigating options to optically switch a soliton. For this, we select the switching mechanism in a graphene-based slab-waveguide, which has been previously shown to support optical spatial solitons [27] (Fig. 1). Graphene is chosen because it fulfills multiple functions simultaneously: (a) it serves as a soliton-generation material, (b) it bears a high intrinsic Kerr nonlinearity, and (c) it allows for nanoscale dimensionality enabling compact designs [10,12]. We note that the modal overlap of graphene is relatively low in a diffraction-limited waveguide, but can approach 1% in plasmonic slot-waveguides [12]. First, we evaluate the crosstalk between two orthogonally directed solitons [Fig. 1(a)] by comparing the transmitted power of a soliton beam with and without a second intersecting soliton. The results confirm a minimal interaction between the orthogonally intersecting in-phase solitons as quantified by a low interaction between the two beams of only 0.035 dB in terms of power at the output. The reason for this is that through the nonlinear Kerr effect, the high-power in-plane field induces an anisotropic increase in the electric permittivity, causing self-confinement of the beam in the direction of propagation. We note that while the used beam intensity is high, 2.25 $\times 10^7$ [V/m], it is below the field breakdown voltage of SiO$_2$, 3 $\times 10^9$ [V/m] [28].

We next investigate the interaction of two parallel solitons propagating at sub-wavelength distances to each other, since we have a high information processing density application in mind [Fig. 1(b)]. Here, the two beams are directed into the graphene monolayer from the same edge and in the same direction. We find that the spatial distribution at the output depends on the phase difference between the two input beams (Fig. 2). Effectively, this phase difference either pulls the output toward one side [i.e., $\pi/4$ phase change, Fig. 2(a)] or splits the output into two beams [i.e., $\pi$ phase change, Fig. 2(c)]. Strong all-optical interaction is a direct result of the soliton property in graphene and the high wavefunction overlap between the two beams being separated by less than one wavelength from each other.

Next, we are interested in evaluating the output’s spatial distribution dependence on the relative separation distance of the two entering soliton beams [Fig. 1(b)] to find the maximum separation between the two output peaks [Fig. 3(a)]. This point would represent an optimal separation distance for switching. Our results show that as the beams are separated the interference between the two beams continues to create a phase-dependent spatial distribution in the output power until the beams are separated by over twice their operating wavelength of 850 nm [Fig. 3(b)]. The peak separation at the output without decreasing FWHM is found near 500 nm.
Lastly, we combine both previous concepts to show spatial switching functionality; to achieve this, we direct two beam pairs along two orthogonal edges of the graphene-oxide heterostructure monolayer [Fig. 1(c)]. Indeed, we find that the minimal crosstalk between the two-pair solitons preserve the phase-dependent spatial distribution at each output (Fig. 4). The beams were simulated in their four potential states: a single pair in phase, a single pair out of phase, two pairs in phase, and two pairs out of phase (Fig. 4). The results demonstrate the independence of the orthogonal pairs of beams; that is, a pair in one state has a minimal impact on the crossing pair regardless of the state of either pair. This is made possible by the tensor nature of the third-order nonlinearity, resulting in anisotropic intensity-dependent adjustments to the refractive index. Such confinement with crossing independence is impossible to achieve in linear isotropic material systems and points to the unique value of spatial optical solitons in dense information processing systems.

To experimentally demonstrate the soliton crossing investigated here, two challenges must be overcome. The first challenge is coupling the source beam into the dielectric-cladded monolayer of graphene. While the electric field enhancement of metallic nanostructures, such as AFM probes in scattering-type scanning near field optical microscopy (s-SNOM) has been used to launch plasmonic waves onto graphene [29,30], the solitons in our simulation were confined by the index of the graphene, not the surface plasmons. It may be feasible to launch the solitons into the graphene monolayer with an AFM probe placed on the edge of the monolayer (z-axis in Fig. 1) using the electric field enhancement on the surface of the AFM probe to excite the in-plane electric field of the graphene layer.

The second experimental challenge is the strong optical absorption of graphene. Using a model for graphene's complex
permittivity [31], there may exist a narrow region around a bias of 0.8 eV, where the complex part of the linear refractive index at 850 nm can be reduced (Fig. 5). Graphene also exhibits a strong nonlinear absorption [32], which may prove more challenging to overcome. However, both nonlinear and absorptive effects in graphene have been shown analytically to be widely tunable [33].

In summary, we have shown that spatial division multiplexing in graphene waveguides is possible when enabled by the independence of orthogonally propagating solitons. We have contrasted this with the dependence between two parallel propagating solitons and combined both concepts to form a two-pair soliton system with independence in each propagation direction. While the switching performance of spatial solitons is high, with deflection occurring at the speed of propagation, on the order of 3 ps [5], modulating the relative phase of the incoming beams sets the limit for the speed of the device. Practical implementation of this device would also require overcoming the challenges of coupling into the thin graphene layer and graphene’s absorption. The context of this Letter is relevant for optical computing and signal processing, where the ability of optical signals to be multiplexed within the same physical space becomes dominant over the density of components. Signal multiplexing has already been achieved to a limited extent in optical systems with wavelength division multiplexing (WDM). Extending the concept of multiplexing to include propagation direction has the potential to create another dimension for footprint reuse in future optical information processing systems.

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