Research Article

Marcus Tamura*, Hugh Morison and Bhavin J. Shastri Inducing optical self-pulsation by electrically tuning graphene on a silicon microring

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Abstract: A mechanism for self-pulsation in a proposed graphene-on-silicon microring device is studied. The relevant nonlinear e ects of two photon absorption, Kerr e ect, saturable absorption, free carrier absorption, and dispersion are included in a coupled mode theory framework. We look at the electrical tunability of absorption and the Kerr e ect in graphene. We show that the microring can switch from a stable rest state to a self-pulsation state by electrically tuning the graphene under constant illumination. This switching is indicative of a supercritical Hopf bifurcation since the frequency of the pulses is approximately constant at 7 GHz and the amplitudes initial grow with increasing Fermi level. The CMOS compatibility of graphene and the opto-electronic mechanism allows this to device to be fairly easily integrated with other silicon photonic devices.

Keywords: graphene; opto-electronic; self-pulsation; silicon photonics.

1 Introduction

Self-sustained pulsations or self-pulsations occur when there is a repetitive ring to a strong stimulus [1]. Selfpulsation has applications in spectroscopy and optical computing [2, 3]. A variety of integrated devices has this behavior and tends to fall into two categories: semiconductor lasers or nonlinear optical cavities. Semiconductor lasers can be classi ed as being either optically injected [4–12] or electrically injected [1, 13–17]. The reader is referred to [18] for an in-depth review. However, most

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nonlinear optical cavity devices are all-optical [19, 20] due to the lack of an electrical injection gain element [21-23]. Without the gain element, achieving optical intensities strong enough to induce nonlinear behavior can be di cult. An electrical input has a lot of bene ts as it is more easily integrable with other systems. This is particularly important for cascadability in large scale systems, where integrated electrical gain is more easily implemented compared to optical gain. Additionally electrical inputs can easily interface with CMOS electronic systems. Previous work uses thermal and free carrier e ects to obtain self-pulsation in a photonic crystal [22] and a microring [20, 21]. However, these devices are limited to MHz speeds because of their reliance on thermal e ects. Faster devices typically use the Kerr e ect and free carriers which operate at the femtosecond and nanosecond time scale, respectively. These two e ects compete against each other due to their opposite signs in silicon, but the free carrier e ect can dominate with higher concentrations in smaller rings [24]. The reason free carriers can create self-pulsation is due to a bifurcation. A bifurcation is a sudden qualitative change in the dynamics of a system when a parameter is smoothly changed. When dynamical systems are perturbed, they typically decay to a nearby constant steady state, also known as a stable xed point. A stable limit cycle describes an area of state space where nearby states limit towards oscillatory behavior. Self-pulsation is fundamentally created by a bifurcation in the eld evolution dynamics that switches trajectories between a stable xed point to limit cycle behavior. A type of bifurcation that can cause this is a supercritical Hopf bifurcation, where by de nition a stable xed point is converted to an unstable xed point surrounded by limit cycle. Bifurcations require nonlinear behavior, so nonlinear materials could enhance self-pulsation; one such material is graphene.

Graphene comes with a few bene ts: Its linear dispersion means it is wavelength independent. It can operate over a large bandwidth because it has no bandgap. It is CMOS compatible [25], which allows for relatively easy integration with other silicon photonic devices. Its absorption tunability is strong since it is related to Pauli

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By applying a bias to the graphene across the aluminum oxide, the graphene can be charged and its Fermi level can be modulated. To nd the distribution of the electric eld in the waveguide a nite di erence eigenmode solver was used. The horizontal electric eld forms the majority of the energy in the mode. The interaction of the light with the graphene is strongest when the electric eld is parallel to the graphene because it is treated as a surface conductivity. We operate the ring in quasi TE-mode and in this way the graphene on top of the waveguide has more in uence than the graphene on the side of the waveguide. Applying a voltage bias to the graphene changes its optical properties; however the overall distribution of the light in the waveguide changes very little. We approximate the optical energy distribution in the waveguide to be constant with changing Fermi level of graphene. Voltage bias does change the e ective refractive index and these e ects are captured in the next section as perturbations. We obtain the unperturbed e ective refractive index, o, from the eigenmode solver when the Fermi level is 0.1 eV. This Fermi level was chosen because the optical behavior of graphene is relatively constant there.

3 The numerical model

Table 2: Simulation parameters.

Symbol	Value	Definition
Q	Ε	Intrinsic quality factor
$Q_{ m e}$	Е	External quality factor
P _{pump}	mW	Input power
λ	nm	Resonant wavelength
δ	ω	Frequency detuning
$ au_{car}$	ps	Free carrier lifetime
n		Unperturbed effective refractive index
$\beta_{\rm Si}$	E - m/W	TPA coefficient for silicon
n _{Si}	E - m / W	Kerr coefficient for silicon
Г	meV	Graphene relaxation rate
W _{sat}	. pJ	Saturation cavity energy
$\sigma_{ m FCA}$. E – m	Free carrier absorption coefficient
$\sigma_{\rm e}$. E — m	Electron dispersion coefficient
$\sigma_{ m h}$. E —	-

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