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Mid-IR Nonlinear Integrated Photonics: Physics and Devices

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***Abstract*— We discuss our recent developments using silicon nanophotonic wires as nonlinear media at mid-IR wavelengths both to observe nonlinear optical physics and to explore specific application.**

***Keywords*- Nonlinear optics, mid-IR, integrated photonics, Silicon photonics.**

I. INTRODUCTION

Photonic research on silicon platforms has attracted much attention over the past several decades because it is envisioned to be an important future foundation for a unified photonic platform. Such a foundation could in principle enable production of most telecommunication components at a low-cost, highly-compact and mass-production-ready fashion [1]. This interest has spurred research into novel application areas based on the components produced using the same CMOS photonics technology, including mid-infrared silicon photonics [2-9], silicon bio-photonics, and other applications.

One particular applications area is that of nonlinear effects in Si photonic wires at telecommunications wavelengths bands, which has been shown to provide a fascinating and useful medium for nonlinear optical physics and applications in data communications. Here we discuss our recent developments using silicon nanophotonic wires as nonlinear media at mid-IR wavelengths both to observe nonlinear optical physics and to explore specific application.

II. NONLINEAR PROPERTIES

Silicon's lowest-order nonlinearity is the third-order nonlinearity or Kerr effect. Considering the high refractive index contrast on the silicon platform, the effective nonlinear parameter for a silicon nanophotonic wire is five orders of magnitude larger than that of an optical fiber (100 $W^{-1}m^{-1}$ vs. 1 $W^{-1}km^{-1}$) [10]. As a result, strong optical nonlinear interaction can be observed in a silicon nanophotonic wire with a length of only a few millimeters compared with several hundred of meters in the case of an optical fiber.

In recent years, various third-order nonlinear effects in silicon nanophotonic wires have been studied [10, 11, 12]. In these studies it has been shown that the nonlinear efficiency in the telecom band is largely suppressed by the optical limiting effect due to silicon's two-photon absorption (TPA) loss as well as its TPA-induced free-carrier absorption (FCA) loss [11]. Although the FCA loss can be drastically suppressed by reducing free-carrier lifetime by means of reverse biasing and ion implantation, the inherent loss of TPA in silicon remains unchanged. However, strong TPA absorption in silicon can be eliminated by shifting the wavelength of operation from telecom to mid-infrared. At 300K, silicon has a bandgap ~ 1.12 eV which corresponds to a linear absorption cut-off wavelength of 1.1 μm. Therefore the cut-off wavelength for TPA in silicon is ~ 2.2 μm. The vanishing TPA for mid-infrared wavelengths beyond 2.2 μm [16], which, coupled with silicon's large nonlinear index of refraction and its strong waveguide optical confinement, enables efficient nonlinear processes in the mid-infrared.

By taking advantage of these nonlinear processes and through judicious use of dispersion engineering in Si photonic wires, we have recently demonstrated a handful of Si mid-IR nonlinear components, including optical parametric amplifiers (OPA) [3], broadband sources [6], a wavelength translator [2] and an optical parametric oscillator [13]. Silicon nanophotonic waveguide's anomalous dispersion design enabled by varying the wire cross-section and/or changing the surrounding materials, providing four-wave-mixing (FWM) phase-matching, enables us to have reported the first demonstration of a silicon mid-IR optical parametric amplifier (OPA) with a net off-chip gain exceeding 13 dB. In addition, by exploiting a new phase-matching scheme with a balanced second and fourth order waveguide dispersion, an OPA with an extremely broadband gain spectrum from 1.9-2.5 μm and >50 dB parametric gain has been demonstrated, upon which several novel silicon mid-IR light sources have been built, including a mid-IR optical parametric oscillator, and a supercontinuum source. Finally, a mid-IR wavelength translation device, capable of translating signals near 2.4 μm to the telecom-band near 1.6 μm with simultaneous 19 dB gain, has been demonstrated.

III. THEORY

The low-loss properties of Si in the mid-IR also lend themselves to being an almost ideal nonlinear medium for studying the physics of pulse propagation in nanowires. Our group has examined these physics using a comprehensive numerical approach first studies at $\lambda \sim 1.55$ μm. Our work includes comparative wavelength studies of parabolic

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self-similar optical pulses [13] and pulse compression [14] in adiabatically tapered Si photonic nanowires (Si-PhNWs).. Our theoretical and computational study is based on a rigorous model that describes the coupled dynamics of the optical field and photo-generated free carriers, as well as the influence of the physical and geometrical parameters of the Si-PhNWs on these dynamics. In addition, we have also examined pulse propagation in many of the components or devices and waveguide structures used in our experimental work, with the intent in these latter cases to understand specific device effects. Thus our study of the enhanced conversion efficiency (CE) and parametric amplification of optical pulses via quasi-phase-matched four-wave-mixing (FWM) in long-period Bragg Si waveguides suggests that, in the anomalous group-velocity dispersion regime, a CE enhancement of > 20 dB, compared to the case of a constant width waveguide, can be easily achieved.

In more detail, our study of generation of parabolic self-similar optical pulses in tapered Si photonic nanowires demonstrates that, in the normal dispersion regime, optical pulses evolve naturally into parabolic pulses upon propagation in millimeter-long tapered Si-PhNWs, with the efficiency of this pulse-reshaping process being strongly dependent on the spectral and pulse parameter regime, in which the device operates, as well as the particular shape of the Si-PhNWs. In addition, our comprehensive analysis of pulse compression in adiabatically tapered Si-PhNWs considers both the soliton and non-soliton pulse propagation regimes. We show that by engineering the linear and nonlinear optical properties of Si- Si-PhNWs through adiabatically varying their width, one can achieve more than 10× pulse compression in millimeter-long waveguides. In both of these studies we compare the response of Si-PhNWs for both $\lambda = 1.55$ μm and mid-IR wavelengths.

IV. Enabling On-Chip IR Components

A final aspect of our work has been to develop new mid-IR components to enable full integration of a nonlinear optical system or subsystem. One of these components is a new approach to on-chip quasi-phase matching. In our case, we wished to use this to enable greater efficiency in connecting the standard telecomm band to the mid-IR.

A second key component is a viable on-chip detector of mid-IR. Our approach to this makes use of ion-implanted Si waveguide photodetectors (PD), which we and others, including the Knight and the Geis Groups, have recently developed to be incorporated into numerous photonic integrated circuits and systems. By implanting Si with a selected atomic species, photodetection from 1550 nm to beyond 1900 nm has been achieved, opening up the ability to incorporate detectors for the telecom band and beyond in integrated Si systems. These devices have been demonstrated with bandwidths > 35 GHz and responsivities < 10 A/W along with error-free data transmission at wavelengths of 1550 nm and 1900 nm. These ion-implanted waveguide PDs have been incorporated in Si photonic devices for power monitoring, wavelength monitoring, thermal tuning, and variable optical attenuation. Recently our group has explored the use of several strategies for extending this wavelength into the mid-IR range.

V SUMMARY

We have presented a comprehensive study of nonlinear mid-IR propagation and propagation devices in Si. This nonlinear medium is both low loss and highly nonlinear in the mid-IR, thus enabling a 'fiber-on-a-chip' capability.

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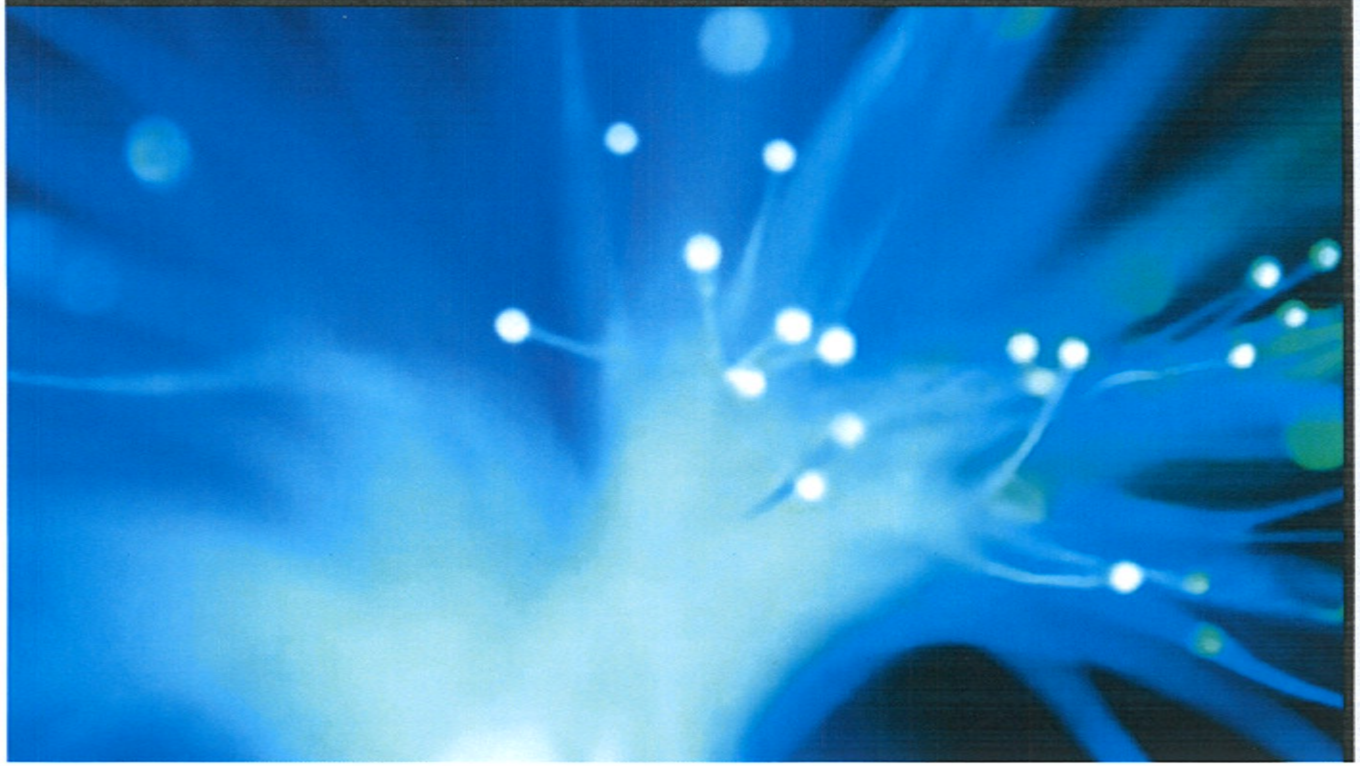

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