Efficient Quasi-Phase-Matched Second Harmonic Generation in Silicon Waveguides

Erman Timurdogan[1,2], **Christopher V. Poulton**[1,2], **Matthew J. Byrd**[1] **and Michael R. Watts**[1]
[1]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Current Affiliation is Analog Photonics, 1 Marina Park Drive, Boston, MA 02210, USA
erman@analogphotonics.com

Abstract: We demonstrate quasi-phase-matched second harmonic generation in silicon waveguides with periodically patterned p-i-n junctions using a field-induced $\chi^{(2)}$. A maximum efficiency of $P_{2\omega}/P_{\omega}^2$=13%/W is measured and multiple signal wavelengths are shown by changing the period.

OCIS codes: (250.3140) Integrated optoelectronic circuits; (190.2620) Harmonic generation and mixing; (230.4320) Nonlinear optical devices.

1. Introduction

A second order nonlinear susceptibility, $\chi^{(2)}$, in a complementary-metal-oxide-semiconductor (CMOS) compatible silicon photonics platform is absent due to the crystalline symmetry of widely available dielectric materials: silicon, silicon nitride, silicon oxide and germanium. This symmetry provides a significant challenge for achieving efficient second harmonic generation in this platform. To induce a $\chi^{(2)}$ in these dielectric materials, stress, charges, or asymmetries around the interfaces of a waveguide can be utilized; however, this resulted in relatively low second harmonic generation efficiencies ($P_{2\omega}/P_{\omega}^2$=0.1%/W [1], 10^{-5}%/W [2]). In these cases, the efficiency was limited by the magnitude of $\chi^{(2)}$, overlap between pump and harmonic waveguide modes, and lack of phase matching between the pump and harmonic signals as opposed to non-centrosymmetric media such as periodically poled lithium niobate (PPLN, $P_{2\omega}/P_{\omega}^2$=204%/W [3]). Therefore, generating and controlling the distribution of $\chi^{(2)}$ to quasi-phase match pump and harmonic signals will be key to enable a versatile and efficient solution.

Although silicon does not intrinsically posses a $\chi^{(2)}$, the third order nonlinear susceptibility, $\chi^{(3)}$, of silicon is large and can be converted to an effective $\chi^{(2)}$ with an applied electric field to break the crystalline symmetry [4]. In this work [5], we generate large electric fields within p-i-n junctions formed in a ridge silicon waveguide to create a large field-induced $\chi^{(2)}$. By patterning these junctions along the length of the waveuide, a periodic field-induced $\chi^{(2)}$ is generated that quasi-phase matches pump and harmonic signals. Using this technique, an electric field dependent second harmonic signal is observed and a maximum second harmonic generation (SHG) efficiency of $P_{2\omega}/P_{\omega}^2$=13%/W at λ_{ω}=2.29μm is measured with a field-induced $\chi^{(2)}$=41pm/V. The period of the p-i-n junction, and thus, the electric field and field-induced $\chi^{(2)}$, is then altered, and multiple quasi-phase-matched harmonic wavelengths spanning from $\lambda_{2\omega}$=1.08μm to λ_{ω}=1.21μm are demonstrated.

2. Device Design and Experimental Results

A cross-sectional illustration of the ridge waveguide is shown in Fig. 1(a). A p-i-n junction is formed with an undoped silicon core. This structure can create a large electric field in the core to induce a $\chi^{(2)}$. For a reverse-biased p-i-n junction, the applied DC electric, E_{DC}^{x}, and optical fields, e_{ω}^{x}, are along the x direction, and the nonlinear displacement

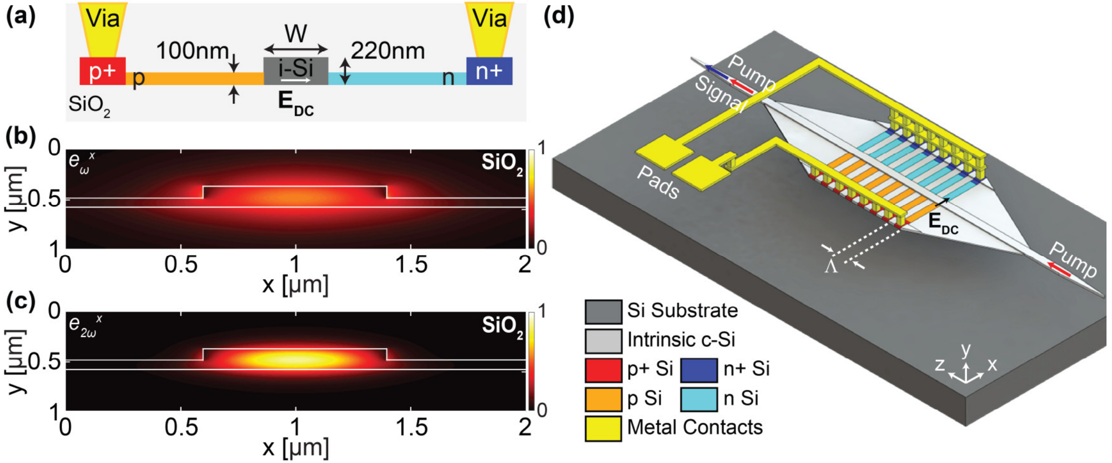

Fig. 1: (a) Dimensions of the $\chi^{(2)}$ silicon ridge waveguide with p-i-n junction. **(b-c)** Fundamental mode of the pump and signal, respectively. **(d)** 3D illustration of the device with silicon ridge waveguide and spatially periodic p-i-n junction to quasi-phase match the pump and signal.

current of interest of isotropic silicon is given by $D = \varepsilon_0\left[\varepsilon_{Si} e_\omega^x \cos(\omega t) + 3\chi^{(3)}_{xxxx} E^x_{DC} e^{x^2}_\omega cos(2\omega t)\right]$, where ε_0 and ε_{Si} are the vacuum and relative silicon permittivities, respectively. The field-induced second harmonic generation (EFISHG) induce a relative permittivity that is related to $\chi^{(3)}$ and E^{x}_{DC}. To induce this relative permittivity, the waveguide is designed to support low loss and highly confined fundamental TE pump and signal modes (Fig. 1(b-c)) that have high overlap between each other and the electric field. However, the propagation constants of these modes are not matched. In order to quasi-phase match these modes, the distribution of the field-induced $\chi^{(2)}$ is controlled by periodically patterning the p-i-n junction throughout the waveguide with a period Λ.

The designed quasi-phase-matched second harmonic generator is illustrated in Fig. 1(d) and the length of the periodically patterned p-i-n junction is 1mm long. To test the device, 25mW of CW pump laser power was coupled into the fundamental TE mode of the ridge silicon waveguide. The SHG signal was recorded as a function of wavelength and applied reverse DC bias to the p-i-n junction spanning from -0.5V to 21V (Fig. 2(a)). The SHG efficiency increased with reverse bias due to the stronger induced electric field, and the maximum SHG efficiency was measured to be $P_{2\omega}/P_\omega^2$=13%/W at a pump wavelength of λ_ω~2.29μm and a reverse bias of V_{DC}=21V. This SHG efficiency matched to a field-induced $\chi^{(2)}$ of 41pm/V, which is comparable to non-centrosymmetric media such as lithium niobate [3]. The location of the field-induced $\chi^{(2)}$ can easily be controlled, and so by changing the period of the p-i-n junction, different quasi-phase-matching conditions can be achieved. In Fig. 2(b), different pairs of p-i-n junction periods and waveguide widths were characterized showing good quasi-phase matching over a wide range of pump and signal wavelengths. This capability to quasi-phase match any desired pump and signal wavelength will allow for efficient SHG in silicon at wavelengths in near and mid-infrared spectrum.

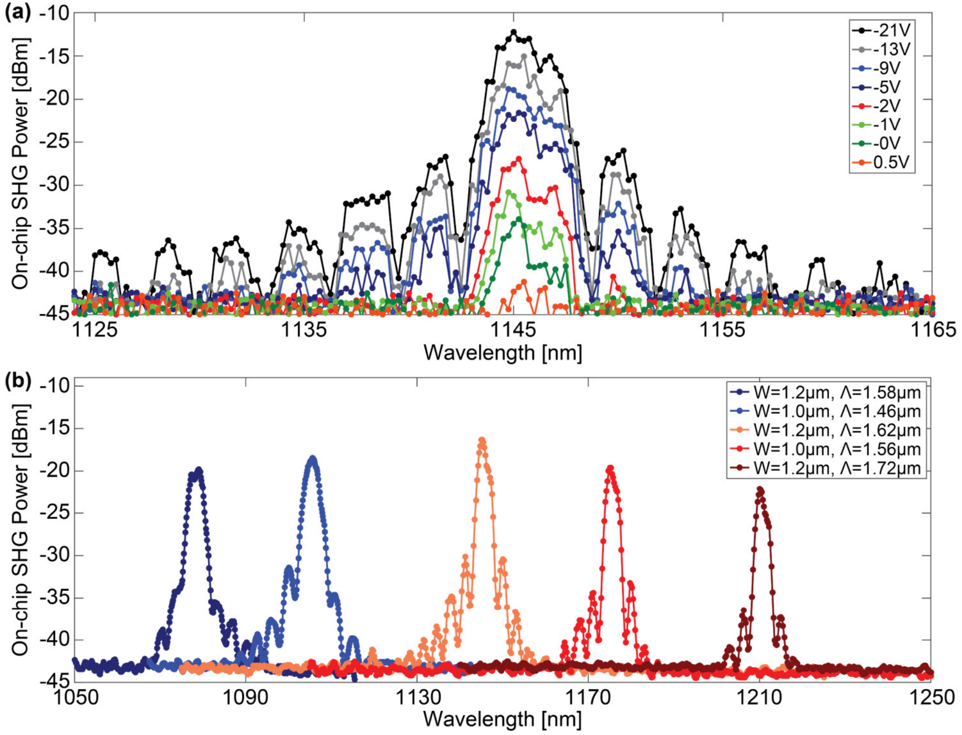

Fig. 2: (a) SHG signal power as a function of input wavelength and applied reverse bias. Inset: SHG efficiency as a function of applied reverse bias. **(b)** SHG signal power as a function of input wavelength for separate waveguides with different widths and p-i-n junction periods.

In conclusion, efficient quasi-phase-matched second harmonic generation in a silicon ridge waveguide was demonstrated using electric fields within periodically patterned p-i-n junctions. A maximum efficiency of $P_{2\omega}/P_\omega^2$=13%/W was measured, corresponding to a field-induced $\chi^{(2)}$ of 41pm/V, which is comparable to non-centrosymmetric media. This large $\chi^{(2)}$ and the ability to quasi-phase match arbitrary waveguide modes allows for a versatile CMOS compatible nonlinear platform.

This work was supported by the Defense Advanced Research Projects Agency (DARPA) E-PHI (HR0011-12-2-0007) and DODOS (HR0011-15-C-0056) projects.

3. References

[1] J. S. Levy, M. A. Foster, L. A. Gaeta and M. Lipson, Opt. Express, vol. 19, pp. 11415-11421, 2011.
[2] M. Cazzanelli, et al., Nature Materials, vol. 11, pp. 148-154, 2012.
[3] Bortz, M. L. et al. IEEE J. Quant. Electron., vol. 30, pp. 2953-2960, 1994.
[4] P. D. Maker and R. W. Terhune, Phys. Rev., vol. 137, pp. A801-A818, 1965.
[5] E. Timurdogan, C. V. Poulton, M. J. Byrd and M. R. Watts, Nature Photonics, vol. 11, pp. 20-206, 2017.