High efficiency SHG in heterogenous integrated GaAs ring resonators

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***Abstract*— We demonstrate the first integrated gallium arsenide (GaAs) ring resonators for second-harmonic generation (SHG). The GaAs-on-insulator platform offers high quality factors exceeding 2×10^5. We demonstrate 4% absolute internal SHG efficiency with a 61-µW pump coupled to the resonator.**

Keywords—Integrated photonics, nonlinear optics

I. Introduction

The second-order nonlinearity ($\chi^{(2)}$) is one of the most important material properties in nonlinear optics and has been widely applied in different areas. In quantum optics, spontaneous parametric down-conversion (SPDC) based on second-order nonlinearity is used for generating entangled photon pairs, and optical parametric oscillators (OPO) provide continuous variables entanglement. In classical optics, three-wave mixing processes are essential in various applications such as nonlinear microscopy, optical-frequency references and short wavelength lasers, among others. Recently, there has been tremendous interest to transfer those nonlinear devices from bench scale setups into photonic integrated circuits (PICs) [1], [2], which significantly reduces the footprint, power consumption, and cost of the system.

However, big challenges remain in order to achieve that goal. First, currently available integrated nonlinear devices cannot be driven efficiently by integrated lasers, since only tens of milliwatts or lower average power is available. Another difficulty is that commonly used nonlinear platforms are not compatible with active devices either in design, fabrication, or integration. As a result, the nonlinear components are still far from being integrated together with lasers, amplifiers and photodetectors on the same chip, but have to be interfaced by either fiber coupling or chip-to-chip butt coupling. This causes a drop of conversion efficiency by orders of magnitude due to the coupling loss, as well as the degradation of the system performance caused by the facet reflection and instability.

To solve this problem, we propose to use GaAs (and/or AlGaAs depending on the required transparency range) as the medium for nonlinear applications on chip. GaAs (AlGaAs) not only has one of the highest nonlinear optical coefficients for both $\chi^{(2)}$ and $\chi^{(3)}$ among commonly used waveguide materials, but also has been widely used as materials in III-V lasers in PICs. Recently, we demonstrated a record high SHG normalized efficiency of 13,000% $W^{-1}cm^{-2}$ in straight waveguides based on a GaAs on insulator platform, one order of magnitude higher than those of previous SHG platforms [3].

In this work, we demonstrate a GaAs ring resonator platform for SHG pumped at 2 µm wavelength. The resonator platform supports a quality-factor exceeding 2×10^5 and shows a pump power depletion by SHG at sub-milliwatts pump power levels. An absolute internal conversion efficiency of 4% is estimated when 61 µW pump power is coupled into cavity. Furthermore, we predict a SHG efficiency beyond 1,000,000% W^{-1} based on these GaAs resonance structures. This work paves the way for ultra-high efficiency and compact nonlinear devices, and for future integration of nonlinear components and active devices in the same PIC platform.

II. Device design and fabrications

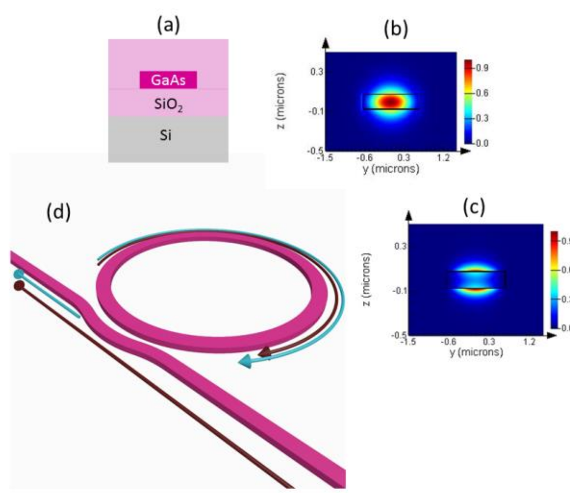

Fig. 1. (a) Cross section of GaAs on insulator waveguide; (b) and (c) mode distributions for the fundamental TE mode at a wavelength of 2 µm and TM mode at a wavelength of 1 µm; (d) schematic structure of ring resonator with pulley coupler.

The schematic drawing of the cross section for the nonlinear waveguide is shown in Fig. 1 (a), whose core material is <001> oriented GaAs film, fully cladded with SiO_2. The SHG process in this work is based on the interaction between TE-polarized pump light and TM-polarized second harmonic (SH) light, employing the non-zero susceptibility elements of the $\chi^{(2)}$ tensor [3]. A key requirement for high

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efficiency SHG is the phase-matching condition. In a <001> oriented GaAs resonator, due to the symmetry for $\chi^{(2)}$ of the material, the phase match condition can be fulfilled by

$$|2m_P - m_{SH}| = 2\,. \tag{1}$$

Here m_p and m_{SH} are the azimuthal mode numbers of pump and SH light, respectively. Based on this, the relation between the refractive indices of pump (n_P) and SHG light (n_{SH}) can be obtained by:

$$n_{SH} = (1 \pm \frac{1}{m_P})n_P \tag{2}$$

This equation indicates that the phase-matching condition in GaAs ring resonators, compared to the modal phase match in straight waveguide, has an offset factor of $1/m_P$ between n_P and n_{SH}. In this work, the radius of the ring resonator is 100 µm and the m_P is around 690, which means that we can design the waveguide to be very similar to the straight waveguide for SHG. The waveguide geometry is 150 nm thick and 1300 nm wide, which fulfills the phase match condition at a wavelength of ~2 µm. The profiles of the TE mode at a wavelength of 2 µm and TM mode at a wavelength of 1 µm are shown in Fig. 1 (c) and (d), respectively. The coupler for ring resonator is a pulley structure with 900 nm wide waveguide, illustrated in Fig. 1 (d).

Our fabrication procedure is based on a heterogenous bonding process to integrate a GaAs film onto a Si wafer with 3 µm SiO_2 top cladding. The waveguides are defined by Deep Ultraviolet (DUV) lithography and dry etching. Detailed information about the fabrication is given in Ref. [3].

III. Experimental Results and Disucssions

The resonators are characterized by injecting 2 µm pump light into the bus waveguide and detecting the transmitted power at the pump and SH wavelength. Figure 2 (a) shows the wavelength response at both wavelengths inside the bus waveguide. We estimate the quality factor of the ring resonator at 2 µm to be higher than 2×10^5, based on the full width half maximum of <10 pm at the pump wavelength resonance. And the quality factor at 1 µm is estimated to be around 5.7×10^4, based on the propagation loss extracted from cutback measurement.

It also can be seen in Fig. 2 (a) that the SHG occurs at the resonance of the pump wavelength. The SH power under different pump power levels is plotted in Fig. 2 (b). The red dashed line with a slope of 2 in log scale corresponds to the non-depleted case. The experimental data points indicate a clear pump power depletion for a pump power of < 1 mW inside the bus waveguide, of which < 200 µW is coupled into the resonator. This indicates that significant absolute frequency conversions take place at very low pump powers.

The external normalized SHG efficiency for this device is around 100%/W. Considering that the ring resonator is highly under-coupled at both pump and SHG wavelength, the internal conversion efficiency is a better parameter for characterizing the potential capability for frequency conversion as would be used in applications. Based on the theory in Ref. [4] and [5], the internal conversion efficiency is extracted by fitting the external efficiency as a function of pump power (Fig. 3 (c)). We estimate that with 0.34 mW pump power inside bus waveguide, 61 µW of it gets coupled into cavity. The internal conversion efficiency in this situation is estimated to be 4%, corresponding to a normalized efficiency around 65,000% W^{-1}.

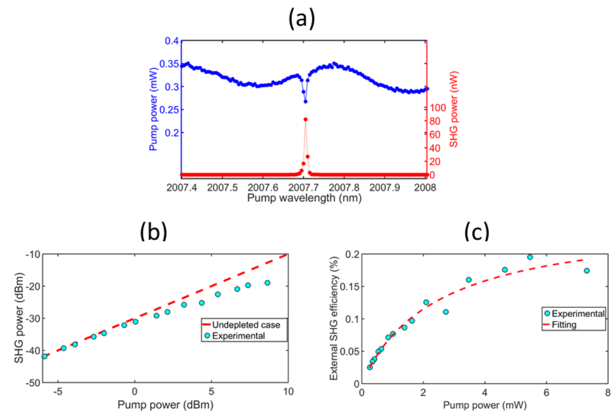

Fig. 2. Experimental results and analysis: (a) pump and SHG power inside bus waveguide as a function of the pump wavelength; (b) dependence of SHG power on pump power, experimental results compared to the case assuming no depletion; (c) dependence of external SHG conversion efficiency on pump power, experimental results and fitting curve.

According to our modeling of the nonlinear optical processes and material parameters involved, by using a 1-mm long racetrack resonator of GaAs on insulator, the expected SHG external normalized efficiency is about 1,080,000%/W. This tremendous conversion coefficient is due to the more efficient utilization of nonlinear parameters along the straight sections. Such strong frequency conversion can provide currently inaccessible on-chip nonlinear processes with extremely strict power budget. Moreover, those nonlinear waveguides can be integrated together with gain mediums (e.g. InAs, InGaAs), which provides a routine to a fully integrated nonlinear PICs on chip. Further, this platform enables studies of classical nonlinear optics in extreme regimes, and the potential for generation and processing of quantum information by extreme nonlinearities.

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