# Near-Visible Flexible Frequency Conversion in Linear Integrated Waveguides

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**Abstract:** We demonstrate frequency conversion of near visible light using Bragg scattering four wave mixing in a low-loss ($\sim 0.02$ dB/cm) silicon nitride waveguide with a Kerr coefficient of $\sim 7.5\ \mathrm{W}^{-1}\mathrm{m}^{-1}$.

## 1. Introduction

The ability to network heterogeneous quantum systems through quantum state preserving frequency conversion could enable new degrees of scalability of linear surface ion traps and other quantum information platforms. [1]. For example, using flexible frequency conversion processes that preserve quantum coherence—such as Bragg scattering four wave mixing (BSFWM)—one may entangle heterogeneous and/or distant atomic, and photonic quantum systems. [2].

Bragg scattering four wave mixing is a nonlinear optical process in which the $\chi^{(3)}$ polarization current produced by two strong pump waves (at frequencies $\omega_{\mathrm{p}}^{(1)}$ and $\omega_{\mathrm{p}}^{(2)}$) induces coupling between signal and idler waves ($\omega_{\mathrm{s}}$ and $\omega_{\mathrm{i}}$)—subject to energy conservation ($\omega_{\mathrm{p}}^{(2)}+\omega_{\mathrm{s}}=\omega_{\mathrm{p}}^{(1)}+\omega_{\mathrm{i}}$), and phase matching conditions ($\mathrm{k}_{\mathrm{p}}^{(2)}+\mathrm{k}_{\mathrm{s}}=\mathrm{k}_{\mathrm{p}}^{(1)}+\mathrm{k}_{\mathrm{i}}$). This process is characterized by a conversion ($\eta$) and system efficiency ($F$)

$$\eta=\frac{4\gamma^2}{\Delta k^2}P_1P_2*\sin^2[\frac{\Delta kz}{2}] \tag{1}$$

$$F=\eta\exp(-\alpha z)=\frac{4\gamma^2\exp(-\alpha z)}{\Delta k^2}P_1P_2*\sin^2[\frac{\Delta kz}{2}], \tag{2}$$

where $\gamma$ is the Kerr coefficient of the waveguide system, $\Delta\mathrm{k}$ is the phase mismatch given by $\Delta\mathrm{k}=\mathrm{k}_{\mathrm{p}}^{(2)}+\mathrm{k}_{\mathrm{s}}-\mathrm{k}_{\mathrm{p}}^{(1)}-\mathrm{k}_{\mathrm{i}}$, z is the interaction length, $\alpha$ is the loss per unit length, and $\mathrm{P}_1$ and $\mathrm{P}_2$ are the pump powers. As indicated by Eq. 2, the system efficiency is degraded by a factor $\exp(-\alpha\mathrm{z})$ relative to the intrinsic conversion efficiency $\eta$.

## 2. Results

We demonstrate Bragg scattering four wave mixing in a 1.2 m spiral silicon nitride waveguide (shown in Fig. 1a) with cross sectional dimensions of 1200 nm x 50 nm. We characterize the efficiency $\eta$ using the nonlinear heterodyne laser spectroscopy setup depicted in Fig. 1b. Two lasers (labelled Laser A, 830 nm and Laser B, 784.5 nm) are used to generate pump frequencies ($\omega_{\mathrm{p}}^{(1)}$ and $\omega_{\mathrm{p}}^{(2)}$, respectively), as well as a blue- and red-shifted signal frequencies at $\omega_{\mathrm{s}}=\omega_{\mathrm{p}}^{(2)}\pm\Omega$. We used an electro-optic modulator (EOM) to bidirectionally split laser B's frequency by $\Omega$ = 60 MHz. These frequencies are coupled through a variable optical attenuator (VOA) (to modulate on-chip optical power) and into the spiral waveguide. By using an acousto-optic modulator (AOM), a portion of laser A is frequency shifted by $\Delta$ = 150 MHz, providing a heterodyne reference which allows us to observe beat notes from the pump lasers ($\Omega$, $\Delta$) and the converted light ($\Delta\pm\Omega$). Using a photodetector, electronic spectrum analyser (ESA), and optical spectrum analyser (OSA) data, we calculated the conversion efficiency $\eta=\frac{\mathrm{I}_{\Delta}-\mathrm{I}_{\Delta-\Omega}}{\mathrm{I}_{\mathrm{p}}^{(2)}-\mathrm{I}_{\mathrm{p}}^{(1)}}$.

Figure 1c plots the observed conversion efficiency $\eta$ as a function of total pump power on-chip, as well as the theoretical trend which shows best agreement for a Kerr coefficient of $\gamma=7.5\ \mathrm{W}^{-1}\mathrm{m}^{-1}$. At a maximum of 0.6 mW on chip, we observe an efficiency of $\sim 2\times10^{-6}$. Through visible light scattering measurements [4] within the 1.2 m spiral waveguide, we also characterize the linear loss of this waveguide system between the wavelengths of 721 nm and 940 nm (Fig. 1a). We find that over the wavelength range of interest, the waveguide exhibits an exceptionally low loss of $< 0.02$ dB/cm. Using this propagation loss, and conversion efficiency we calculated a total system efficiency of $\sim 10^{-6}$ at 0.6 mW on-chip power.

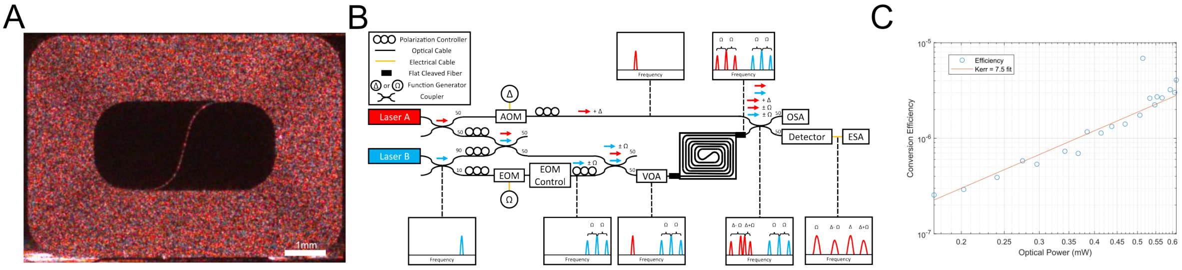

Fig. 1. a) Image of light coupled into the spiral waveguide. b) Experimental setup: we coupled laser A light (pump 1), laser B light (pump 2), and EOM (with frequency Ω) laser B light (signals) into a VOA. The output of the VOA is coupled into a photonic integrated circuit (PIC) containing a 1.2m spiral waveguide. Throughout this waveguide, BSFWM converts EOM laser B light (signals) to frequencies Ω from laser A light (idlers). The output of this PIC was coupled with AOM laser A light. This light is collected by an OSA, and a heterodyne detector (measured by an ESA). c) By modulating the attenuation of the VOA, we modulated on-chip power, and measured the conversion efficiency. This allows us to estimate the system's Kerr coefficient.

## 3. Discussion

Utilizing a 1.2 m long waveguide with low on-chip pump power ($\sim 0.6$ mW) allows us to characterize an estimated conversion efficiency for high on-chip power. At higher on-chip power this frequency conversion can occur with higher efficiency over shorter waveguide lengths, making this technique more practical for integration with additional photonic and quantum micro-systems. The conversion efficiency of this non-resonant system is limited only by optical propagation loss and optical power damage threshold. We expect that this ultra-low loss silicon nitride platform may provide a route to near unity system efficiency utilizing improved fiber to chip coupling, higher pump powers, and pulsed operation. We calculate that with the current waveguide, we may achieve near unity system efficiency in as little as $\sim 11$ cm at 1 W of on-chip pump power. This projected system efficiency compares favorably to demonstrations in resonant structures [5] but has the bandwidth advantages and flexibility inherent to linear (non-resonant) devices.

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