Selective phase-matched Bragg scattering for single-photon frequency conversion in a nonlinear waveguide

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Abstract

We describe a design for phase-matched Bragg scattering for single-photon conversion between two arbitrary frequencies. The bandwidth of the Bragg scattering process is calculated and immunity against competing processes is discussed.

Bragg scattering is a four-wave mixing process where a signal beam is scattered into an idler beam via the refractive index grating generated by the interaction of two strong pump beams in a nonlinear medium. Recently, Bragg scattering has been explored for quantum frequency conversion because it avoids excess noise and preserves the quantum state of the frequency converted photonic state [1,2]. Combined with time lens technique [3], Bragg scattering can be used to frequency convert the photonic wavepacket and impedance match it to a resonance simultaneously, enabling exchange of quantum information between different quantum platforms such as quantum dots and ions.

In the Bragg scattering process, two pump beams (pump 1 and pump 2) are used to convert the signal photon (s) to the idler photon (i). Energy and momentum conservation requires that the frequency and wave vector differences between the signal beam and pump 1 matches the differences between the idler beam and pump 2, described by

$$\omega_s - \omega_{P1} = \omega_i - \omega_{P2} \tag{1}$$
$$k(\omega_s) - k(\omega_{P1}) = k(\omega_i) - k(\omega_{P2}), \tag{2}$$

where ω is the frequency and k is the wavevector. Normally, the phase-matching condition can only be satisfied in the vicinity of the zero-dispersion-frequency ZDF ω_0, where k is approximately linear with ω. However, the use of two pump beams in Bragg-scattering-based frequency-conversion systems gives more degrees-of-freedom for phase-matching control. As shown in Fig. 1(a), by using a symmetric frequency arrangement about ω_0, phase matching can be achieved for fairly large frequency discrepancies for an idealized fiber with vanishing 4th and higher-order dispersion. In realistic fibers, suitable pump frequencies still can always be found given that k is a smooth and monotonic function of on both side of ω_0, which is valid for the case of a waveguide with only one ZDF. Figure 1(b) gives an example of phase matching in a phonic crystal fiber (LMA-5 from NKT Photonics), which has non-zero 4th and higher-order dispersion. Pump beams with wavelengths of 1562 nm and 728 nm are used for frequency translation between the wavelengths of 1550 nm and 725 nm.

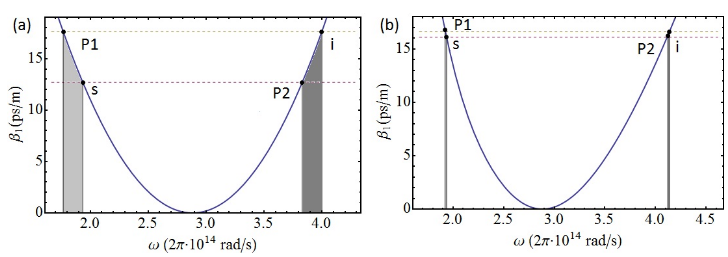

Fig. 1: Phase matching of the Bragg scattering process using a symmetric frequency arrangement about the ZDF in a nonlinear waveguide without 4^{th} and higher-order dispersion (a) and in the PCF LMA-5 (b). The shaded areas illustrate the wavevector differences and the width of these areas show the frequency differences.

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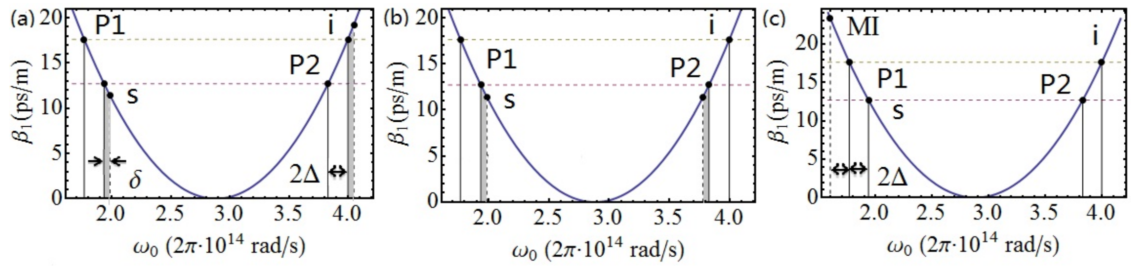

Fig. 2: Phase-mistaching diagram for Bragg scattering ((a) and (b)) and the competing process MI (c). The shadowed areas show the change in k

While its always possible to achieve phase matching for conversion between two arbitrary frequencies in this region, the bandwidth and immunity to competing processes vary substantially. The bandwidth of Bragg scattering is calculated for two case. In one case (Fig. 2(a)), two narrow band pump beams convert a broadband signal photon to a broadband idler photon. Here an off-center frequency component of the signal beam $\omega_s + \delta$ is translated to the off-center frequency component of the idler beam $\omega_i + \delta$, the phase-mismatch term is expressed as

$$\begin{aligned} \Delta kL &= L(k(\omega_s+\delta) - k(\omega_s) - (k(\omega_i+\delta) - k(\omega_i))) \\ &\approx L\delta(\beta_1(\omega_s) - \beta_1(\omega_i)) \\ &\approx L\delta\Delta(\beta_2(\omega_a) - \beta_2(\omega_b)), \end{aligned} \tag{3}$$

where L is the length of the waveguide, β_1 and β_2 are first and second order of dispersion, $2\Delta = \omega_s - \omega_{P1} = \omega_i - \omega_{P2}$, $\omega_a = (\omega_s + \omega_{P1})/2$, and $\omega_b = (\omega_i + \omega_{P2})/2$. Setting $\Delta kL = \pi$, the bandwidth is found to be

$$BW = \frac{\pi}{L\Delta|\beta_2(\omega_a) - \beta_2(\omega_b)|}. \tag{4}$$

We see that the bandwidth of the Bragg scattering process is inversely proportional to the frequency discrepancy Δ in this case. To use this process in a time lens system, we must consider the case where a broadband pump is chirped with the broadband signal photon to generate a narrowband idler photon [3] (Fig. 2(b)). Similarly, the bandwidth is found to be

$$BW = \frac{\pi}{L\Delta|\beta_2(\omega_a) + \beta_2(\omega_b)|}, \tag{5}$$

Note that β_2 tends to be similar and opposite in sign at ω_a and ω_b so that the bandwidth of Bragg scattering is increased in this case. As an example, the bandwidth is increased by a factor of 3 for the frequency conversion in the LMA-5 shown in Figure 1(b).

For a practical single photon frequency converting system, the bandwidth of the converting channel needs to match that of the signal photon wavepacket. To ensure large bandwidth, Δ needs to be small, which limits the region of efficient conversion either to the vicinity of the signal photon frequency or to the vicinity of the frequency at the other side of ω_0 where group velocity matches. However, Δ cannot be set too small otherwise competing effect such as the modulation instability (MI) becomes significant. The phase-matching term of the MI scales as $\Delta k_{MI}L = L\beta_2(\omega_{P1})4\Delta^2$. By setting $\Delta \sim 2\pi\times1.5$ THz, MI is sufficiently suppressed.

In conclusion, we find that phase matching for Bragg scattering can be realized for fairly large frequency differences using a symmetric arrangement about ω_0. The bandwidth of Bragg scattering is inversely proportional to frequency difference Δ. However, Δ should be kept larger to the BW of the Bragg scattering process in order to efficiently suppress competing processes such as the MI.

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