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Fourier Analysis of Quasi-phase Matching Devices for WDM

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Abstract: Since the introduction of wavelength division multiplexing system, the capacity of the optical fibers to carry data was immensely increased. High speed and efficient data transfer thence made possible. Further, the use of quasi-phase matching devices enables us to achieve wavelength division multiplexing with negligible inter symbol interference and cross talk. In this study, we present a theoretical model using Fourier transform to analyze the spectral response of the periodic and aperiodic QPM devices.

Key words: Optical frequency converter, second harmonic generation, quasi-Phase matching

INTRODUCTION

Wavelength conversion is reckoned to be the primal technology for wavelength division multiplexed networks as it enhances the routing of optical and network properties such as re-configurability, non-blocking capability and wavelength reuse (Yoo, 1996; Almeida *et al*., 2004; Sotobayashi *et al*., 2002). Thus, a device which is capable of translating the wavelength of a signal from one to another, falling within the bandwidth of an Erbium-Doped Fiber Amplifier (EDFA) happens to be extremely desirable and necessary. As a result there has been a lot of research over the Quasi-Phase Matching (QPM) devices, in order to implement compact and effective coherent light sources. Over the past few decades, research on cascaded second-order nonlinear interactions in QPM has been growing fast to satisfy the needs of high data rate and large bandwidth optical networks. Achieving wavelength broadcasting in these QPM devices is also useful for several applications such as video distribution and teleconferencing (Shen *et al*., 2009; Sohler *et al*., 2009).

This article explains in detail regarding the second harmonic response of the periodic and aperiodic QPM devices using Fourier analysis, thereby giving a better picture to utilize it as a source for WDM network.

WAVELENGTH DIVISION MULTIPLEXING

This technique allows several optical signals to be channelled along a single fiber at the same time. Also it enables the fiber to be used for duplex communication of the optical signals. It is attained by employing different wavelengths for each transmission and can be implemented on single mode or multimode fibers using laser as a carrier. Thus wavelength division multiplexing allows simultaneous transfer of optical signals from different users through the same fiber.

QUASI-PHASE MATCHING

QPM is a method for achieving efficient energy transfer between interacting waves in a nonlinear process which was first proposed by Armstrong *et al*. (1962). The practical form of this technique is based on a spatial modulation of the nonlinear properties along the interaction path in the material. Such spatial modulation can be obtained in ferroelectric crystals by periodically altering the crystal orientation so that the effective nonlinearity changes according to the orientation. As a result of which interacting waves still propagate with different phase velocities but when the net phase mismatch attains π, the sign of the driving nonlinear susceptibility is also inverted so that the phase difference is “reset” to zero. This produces a step-wise increase in the output power along the length of the crystal as shown in Fig. 1. Thus, the highest conversion efficiency is obtained when the periodicity of the modulation corresponds to $2l_c$, where, l_c is the coherence length, denoting first-order QPM.

A practical approach in a ferroelectric crystal such as $LiNbO_3$ requires constituting the regions of periodically inverted spontaneous polarization domains. Although quasi-phase-matching has lower conversion efficiency than perfect phase-matching, as shown in Fig. 1 it brings useful flexibility into optical parametric processes. The main advantages of QPM is that it allows the use of any convenient combination of polarizations in the nonlinear

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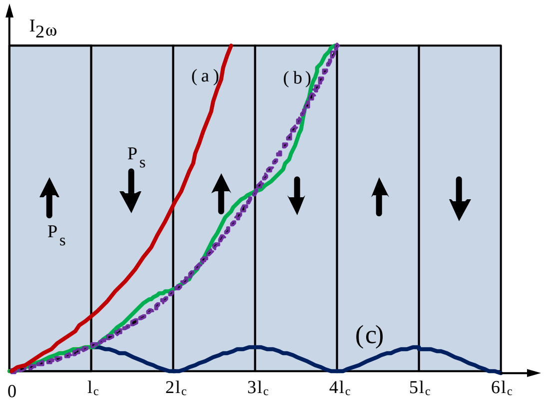

Fig. 1: Increase in the second harmonic intensity with distance in a nonlinear crystal, due to the effect of phase matching (a) Ideal phase-matched interaction (b) First order QPM by alternating the sign of the spontaneous polarization for every coherence length (l_c) of the interaction and (c) Non-phase-matched interaction

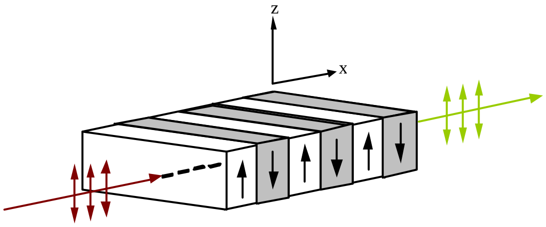

Fig. 2: Periodic QPM device of Type-0 phase matching condition

interaction, including the case where all waves are co-polarized. Co-polarized interactions have the largest nonlinear susceptibility in many materials and are necessary in cases when only optical waves of one polarization are supported in a QPM device.

Periodic QPM devices: They have uniformly spaced domains with reversed polarization as shown in the Fig. 2.

Aperiodic QPM devices: They have unequal domains. The size of those domains can be varied as per our requirement. Here, we discuss an aperiodic device called as phase reversal QPM as shown in Fig. 3. The phase reversal QPM structure is similar to the ideal periodic structure, except that it has an aperiodic domain of width Λ at the middle of the device.

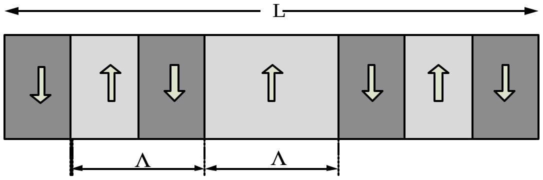

Fig. 3: Schematic of the phase reversal QPM device

Such QPM devices are one among the recent developments in the field of WDM networks as the peak intensity and the separation between the peaks can be engineered by modifying the domain size. Further, Yamawaku *et al*. (2006) proposed a minimum crosstalk multiple channel wavelength conversion idea based on a parametric process by simultaneous wavelength translation of over 25 GHz spaced 103 channels×10 Gbps (1.03 Tbps) wavelength-division multiplexed signals using a Lithium Niobate QPM waveguide.

FOURIER TRANSFORM ANALYSIS

The basic hypothesis of QPM has been discussed by various authors, however, the spectral response and efficiency characterization of several devices like, phase reversal, slanted domain structure, apodized and various aperiodic QPM devices are not yet studied in detail. Hence, we are developing a theoretical model using Fourier transform to analyze the second harmonic spectral response of these devices which can be used efficiently for wavelength division multiplexing schemes. In this study, we have proposed a theoretical model for two types of QPM devices such as periodic and phase reversal.

For our theoretical model, we presume minimum conversion efficiency, be it the CW or long-pulse interaction and negligible losses for the fundamental or even the second harmonic waves. The rudimentary slowly varying amplitude equation controlling the rise in the second harmonic field under such conditions (Fejer *et al*., 1992), is given by:

$$\frac{dA_2}{dz} = i\kappa A_1^2 e^{-i\Delta kz} \qquad (1)$$

where κ is directly proportional to the effective nonlinear optical coefficient d_{eff} and:

$$\Delta k \equiv k_2 - 2k_1 = \frac{4\pi}{\lambda}(n_2 - n_1)$$

for negligible reduction in the fundamental wave, the above Eq. 1 can be directly integrated to give a sinc-form of spectrum if κ is constant in the medium. In case of QPM, κ is not a constant but κ = κ(z). Even in this case, the above equation can be integrated.

Let Δk = 2πq, then:

$$A_2(q) = iA_1^2 \int \kappa(z) e^{-i2\pi qz} dz = iA_1^2 \Im[\kappa(z)] \quad (2)$$

In the first case, we consider the periodic QPM device for analysis. Taking only the 1st order QPM, κ(z) can be expressed as:

$$\kappa(z) = D\,\mathrm{rect}\left(\frac{z - \frac{L}{z}}{L}\right) \sin\left(\frac{2\pi z}{\Lambda}\right) \quad (3)$$

where, D is a constant which is directly proportional to the effective nonlinear optical coefficient and L is the device (poled) length. Then, the second harmonic amplitude Eq. 2 is:

$$A_2(q) = A_1^2 \frac{D}{2} L \left[\sin c\left\{L\left(q \pm \frac{1}{\Lambda}\right)\right\} e^{i\pi L\left(q \pm \frac{1}{\Lambda}\right)}\right] \quad (4)$$

The Eq. 4 can be used to analyze the spectral response of the periodic QPM device. Further, we extended our analysis for calculating the spectral response of the phase reversal QPM device. The length of the QPM device is L, an aperiodic domain has been introduced in the middle (L/2) of the device. So, the phase of the second harmonic wave is reversed by 180° (Pandiyan *et al*., 2009). Hence, the generated second harmonic wave misses the phase matching and produces two peaks near the phase matching point.

The Fig. 4 depicts the spectral response of both periodic and phase reversed QPM devices. The second harmonic amplitude of the phase reversal QPM device can be written as:

$$A_2(q) = iA_1^2 LDe^{i\pi L\left(q \pm \frac{1}{\Lambda}\right)} \left[\frac{\sin^2\left\{\frac{\pi}{2} L\left(q \pm \frac{1}{\Lambda}\right)\right\}}{\frac{\pi}{2} L\left(q \pm \frac{1}{\Lambda}\right)}\right] \quad (5)$$

Figure 1b is our area of interest which can be used for WDM procedures. The distance between those two peaks can be adjusted according to the bandwidth used. It can be easily and efficiently achieved by altering the domain length and other such parameters of the QPM device.

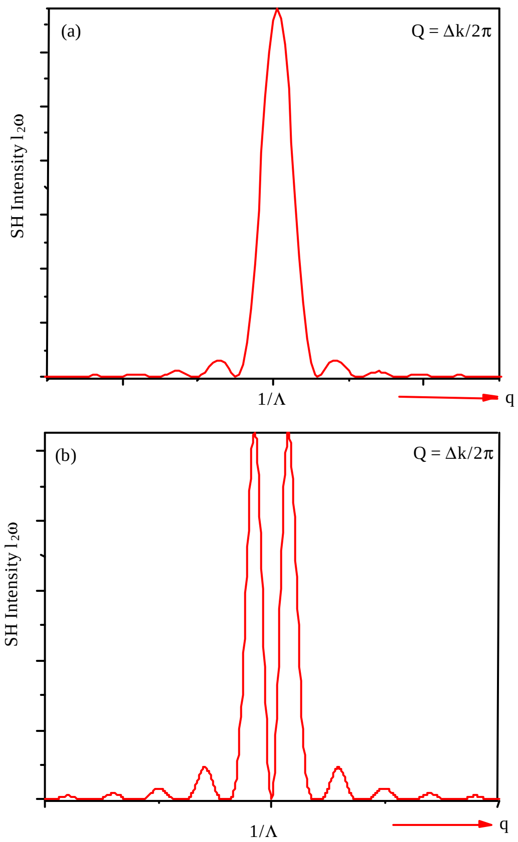

Fig. 4(a-b): Second harmonic intensity spectrum for (a) periodic and (b) phase reversal QPM devices

CONCLUSION

Fourier analysis is an easy and accurate tool for evaluating the second harmonic spectral response of QPM devices. The spectral response of the periodic and phase reversal QPM devices are analyzed in this study. The dual peak nature is attributed to the phase reversal due to the aperiodic domain in the center of the QPM structure which can be used for WDM operation. Further, apodized QPM, slanted domain QPM and other aperiodic QPM structures are in progress.

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