

Research on QPM and Its Cascaded Structure Applied in FOPA

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Abstract: *In the research of optical communication, Optical Parametric Amplification (OPA) has been an important point. As a Four Wave Mixing (FWM) effect based nonlinear process, OPA also requires Phase Matching (PM). Rigorous PM in practical research requires extremely harsh conditions. Quasi Phase Matching (QPM) and its cascaded structure can solve that problem, which would construct an overall phase matching. In the first part of this thesis, a QPM mechanism of segmented High NonLinear Fibre (HNLF) and inserted phase shifter for pumps, was proposed in application of FOPA. The phase shifters would “correct” the phase mismatching after every amplified signal by HNLF section. In this structure the phase matching was always kept in the vicinity of the initial matching value. The signal gain was flatter, and 6.4-9.5 dB higher than that of the non-QPM structure. In second part, a cascaded FWM+OPA structure was used to realize the copier-FOPA according to the cascaded QPM scheme. In the copier part, the information of signal wave was copied into the generated idler wave, before the signal light was amplified. Not only the copy, a 160 nm (Phase Insensitive, PI)/170 nm (Phase Sensitive, PS) gain bandwidth was obtained, which improved greatly comparing to that of the conventional. In FOPA part, the signal flatter gain decreases by approximately 14 dB (PI)/15 dB (PS), with fluctuation down to <0.1 dB (PI) / <0.2 dB (PS). The gain bandwidth decreases to 135 nm (PI) / 150 nm (PS), which is tens of nanometers wider than conventional FOPA.*

Keywords: *FOPA, QPM, WC, cascaded structure, gain.*

1. Introduction

Optical Parametric Amplification (OPA) is an important application based on Four-Wave Mixing (FWM). It is becoming very promising in the research of all optical network system. Compared to other optical amplifications, OPA can reduce the

influence of phase jitter, reduce the noise to 0 dB theoretically, suppress the modulation instability, and regenerate the phase of signal wave, et al. OPA can be realized both in fibre and other waveguide like Semiconductor On Insulator (SOI). In this thesis, the OPA research of bandwidth and noise are all based on fibre.

Conventional highly efficient FWM effect needs the Phase Matching (PM), accurately. However, practical result shows the theoretical requirement is strictly limited. Quasi Phase Matching (QPM) technique comes to the research point in decades, in order to overcome that limitation [1, 2]. First introduced by Armstrong Blembergen et al. [3] in 1962, QPM technology refers to the adjustment of the relative phase among the light waves in the process of transmission, either periodically or non-periodically. It is equivalent to a mechanism of “correction”. Even phase mismatches badly, QPM can compensate the deterioration by adjusting the phases. Therefore, comparing to the conventional PM technology, QPM is more feasible and flexible. Moreover, various QPM solutions can be designed by different parameter demand.

In previous studies, QPM is the periodic modulation of crystal nonlinear susceptibility to compensate the phase mismatch caused by refractive index dispersion. In other word, QPM realize in periodically poled crystal. In following studies, QPM is not limited to the periodic propagation properties of crystals any more. By constructing suitable light path and device, QPM can be achieved in form of sectional phase matching.

In the first part of this thesis, a QPM structure will be designed in FOPA. In the second part, a cascaded structure of Wavelength Conversion (WC) and FOPA which similar to QPM is designed to realise a better gain performance than conventional FOPA.

2. Phase matching in OPA

Take a typical one signal (input), one pump (input), two idler wave (sideband, output) model as example. The analytic expression of propagation field in fibre can be variable separated as

$$(1) \quad E(x, y, z) = f(x, y)A(z) = \frac{1}{2} f(x, y) [A_p(z) \exp j(\beta_p z - \omega_p t) + A_s(z) \exp j(\beta_s z - \omega_s t) + A_i(z) \exp j(\beta_i z - \omega_i t) + c.c.]$$

For not confused with the idle wave i , j represents the imaginary unit; $f(x, y)$ is the transverse distribution; $c.c$ represents complex conjugation which is negligible in calculation. With the attenuation part neglected, respective amplitude coupling equations can be derived as:

$$(2) \quad dA_1/dz = j\gamma \left[|A_1|^2 A_1 + 2(|A_2|^2 + |A_3|^2 + |A_4|^2) A_1 + 2A_3 A_4 A_2^* \exp(j\Delta\beta z) \right],$$

$$(3) \quad dA_2/dz = j\gamma \left[|A_2|^2 A_2 + 2(|A_1|^2 + |A_3|^2 + |A_4|^2) A_2 + 2A_3 A_4 A_1^* \exp(j\Delta\beta z) \right],$$

$$(4) \quad dA_3/dz = j\gamma \left[|A_3|^2 A_3 + 2(|A_1|^2 + |A_2|^2 + |A_4|^2) A_3 + 2A_1 A_2 A_4^* \exp(j\Delta\beta z) \right],$$

$$(5) \quad dA_4/dz = j\gamma \left[|A_4|^2 A_4 + 2(|A_1|^2 + |A_2|^2 + |A_3|^2) A_4 + 2A_1 A_2 A_3^* \exp(j\Delta\beta z) \right],$$

where the nonlinear coefficient $\gamma = 2\pi n_2 / \lambda A_{\text{eff}} = n_2 \omega / c A_{\text{eff}}$, n_2 is the effective refractive index, A_{eff} is the effective mode-field area. The first item on the right side of the equations represents *self-phase modulation process*, while the second represents *cross phase modulation process*. The third item is the parametric process, which realizes the optical parametric amplification. At a power standpoint, it expresses the energy transfer among the waves.

We can solve the analytical solution of input waves in (2) and (3):

$$(6) \quad A_1(z) = \sqrt{P_1} \exp[j\gamma z (P_1 + 2P_2)],$$

$$(7) \quad A_2(z) = \sqrt{P_2} \exp[j\gamma z (P_2 + 2P_1)].$$

Let $n = 1, 2, 3, 4$. Then (2)-(5) can be rewritten as [4]:

$$(8) \quad dP_{1,2}/dz = -2\gamma \sqrt{P_1 P_2 P_3 P_4} \sin \theta,$$

$$(9) \quad dP_{3,4}/dz = 2\gamma \sqrt{P_1 P_2 P_3 P_4} \sin \theta,$$

where the relative phase difference is

$$(10) \quad \theta(z, t) = \Delta\beta z + \phi_1(z) + \phi_2(z) - \phi_3(z) - \phi_4(z) + \omega_1 t + \omega_2 t - \omega_3 t - \omega_4 t.$$

Partial derivation of (10) will be

$$(11) \quad \begin{aligned} \partial\theta/\partial z = & \Delta\beta + \gamma(P_1 + P_2 - P_3 - P_4) + \\ & + \gamma \left[\sqrt{P_1 P_2 P_3 / P_4} + \sqrt{P_1 P_2 P_4 / P_3} - 4\sqrt{P_3 P_4} \right] \cos \theta, \end{aligned}$$

where $\Delta\beta$ represents the linear phase shift, while

$$\gamma(P_1 + P_2 - P_3 - P_4) \text{ and } \gamma \left[\sqrt{P_1 P_2 P_3 / P_4} + \sqrt{P_1 P_2 P_4 / P_3} - 4\sqrt{P_3 P_4} \right] \cos \theta,$$

represent the nonlinear phase shift.

According to (8) (9) and (11), by changing the relative phase difference:

when $0 < \theta \leq \pi/2$, $dP_{1,2}/dz < 0$ and $dP_{3,4}/dz > 0$; power flows from pumps to signal and idler waves; that is the process of OPA;

when $-\pi/2 \leq \theta < 0$, $dP_{1,2}/dz > 0$ and $dP_{3,4}/dz < 0$; power flows in a counter direction, where the power of signal attenuates.

Thus, to fulfill the amplification of signal, θ should stay around $\pi/2$, which means $\cos \theta \approx 0$. Equation (11) can be simplified in condition of intense pump ($P_{1,2} \gg P_{3,4}$):

$$(12) \quad \partial\theta/\partial z = \Delta\beta + \gamma(P_1 + P_2 - P_3 - P_4) \approx \Delta\beta + \gamma(P_1 + P_2) = \Delta\beta + \gamma P_p = \kappa,$$

where κ is the total phase mismatch (phase matches totally when $\kappa = 0$).

3. A cascaded structure of QPM technique with HNLF and phase shifter for FOPA

3.1. Structure

Narrow gain bandwidth and peak-shape gain spectrum [5] are always the limitations in the current FOPA research. One factor limiting flat broadband gain mainly refers to phase mismatch, caused by dispersion instability along the propagation direction, is more likely to occur in fibre than in semiconductor (such as Semiconductor On Insulator, SOI). QPM is more urgent to achieve in fibre [6]

The conventional QPM technique research mostly focused on the periodic phase mismatch compensation mechanism caused by the change of the crystal structure. Being different from periodic nonlinear optical crystal with second order nonlinear susceptibility $\chi^{(2)}$, there is only third-order nonlinear susceptibility $\chi^{(3)}$ in fibre. However, QPM can be realized in fibre by changing the phases. Here the degenerated form of (10) can explain the scheme

$$(13) \quad \Phi(z) = \phi_s + \phi_i - 2\phi_p + \left(\beta_{\lambda_s} + \beta_{\lambda_i} - 2\beta_{\lambda_p} \right) z.$$

A cascaded structure can manage $\Phi(z)$, shown as in Fig. 1. High NonLinear Fibre (HNLF) or Photonic Crystal Fibre (PCF) is a proper selection for FWM process. The theory of this structure is that a pump phase shifter forces $\Phi(z)$ returning zero after a section of HNLF or PCF. The phase shifter shifts only the phase corresponding to the wavelength of the pump wave. In the whole process, $\Phi(z)$ is managed to keep below a threshold ($<\pi$), so that the phase mismatch is small enough to achieve high gain.

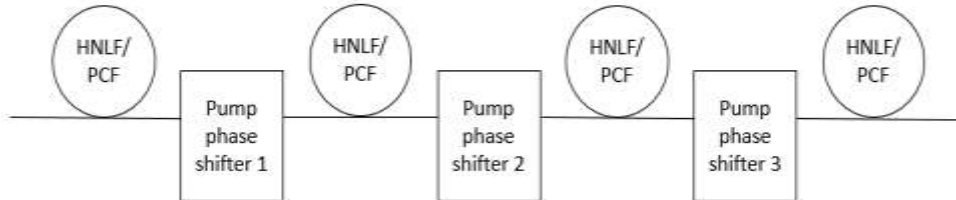


Fig. 1. The cascaded QPM to realize FOPA

3.2. Results and analysis

The parameters used in the simulation are as followed.

The pump wavelength and the zero dispersion wavelength of fibre $\lambda_p = \lambda_0 = 1565$ nm. The signal wavelengths $\lambda_{s1} = 1540$ nm, $\lambda_{s2} = 1550$ nm and $\lambda_{s3} = 1560$ nm, for comparing the performance. The pump power $P_p = 32$ dB.m. The signal power $P_s = -20$ dB.m. The length of every HNLF (or PCF) section $L_i = 50$ km, $i = 1, 2, 3, 4$ (which means three pump shifters).

The relative phase varying along the transmission comparing to non-QPM situation is shown in Fig. 2.

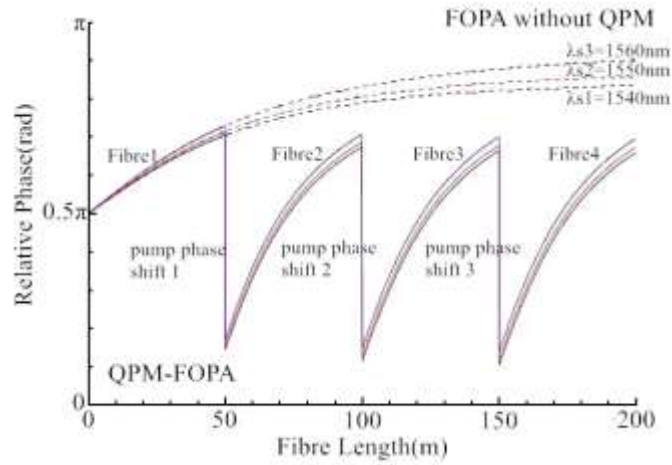


Fig. 2. The comparison of relative phase between conventional FOPA and QPM-FOPA

According to (12) and (13), the initial relative phase $\Phi(0)$ was set to be 0.5π . The pump phase shifter “correct” the phase relation, timely. By comparing the phase characteristic of different signal wavelengths of 1540 nm, 1550 nm and 1560 nm, both in QPM and conventional FOPA, Fig. 2 shows the following results:

(1) In conventional FOPA, the relative phase shifts upward to π (0.9π or so), while severe phase mismatch will cause the deterioration of signal amplification. With the increase of the transmission distance along the optical fibre, the phase shift between different wavelengths will show obvious difference. That is a limitation of the amplification bandwidth.

(2) Because of the pump shift when relative phase reaches a certain value, the phase is “forced” to carry out a matching, to keep it around the initial 0.5π , which is a necessary condition of FOPA phase matching. The signal gain varying with transmission also confirms the two points above, as shown in Fig. 3.

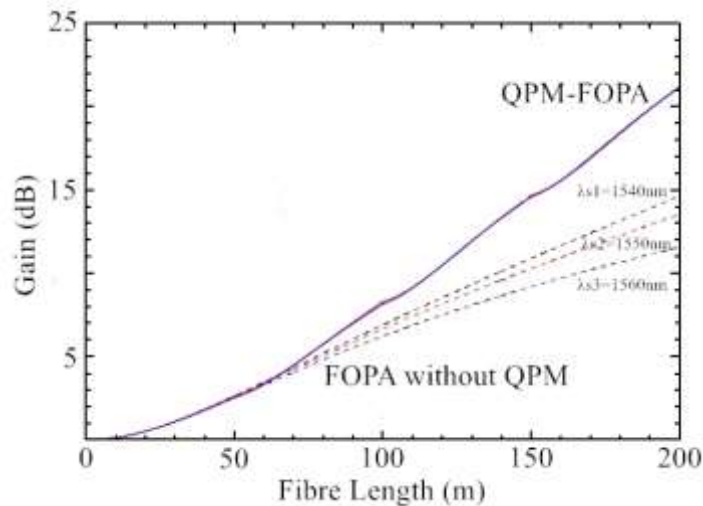


Fig. 3. The comparison of signal gain between conventional FOPA and QPM-FOPA

Fig. 3 shows the following results:

(1) As the transmission characteristic differs from the corresponding wave lengths along the fibre, the relative phase among signal, pump and idler waves will increase rapidly. Then the phase mismatching will be quite different from each other. The signal gains appear different slope. With the “correction” of QPM shift the pump phase uniformly, signal waves with different wavelengths keep the same growth, which present a flat gain in output.

(2) By the sectional compensation of phase matching, QPM-FOPA provides a higher gain than convention. Shown in Fig. 3, in a 200 m transmission length, the gain of QPM-FOPA is 6.4-9.5 dB higher than that of conventional FOPA.

4. A cascaded structure of WC and OPA for FOPA

4.1. Structure

The research in recent years classified OPA into Phase Sensitive (PS-OPA) and Phase Insensitive (PI-OPA). PI-OPA amplifies all the waves on demand. PS-OPA[7-9] is the process in which waves with the same phase to signal are amplified, while in which waves with the phase different from signal are not amplified; or even been eliminated. If the phase noise of signal wave is eliminated in amplification, PI-OPA will play an important part in the performance of improving deteriorated signal.

Generating the idler wave before parametric amplification is an effective technique in PS-OPA. Fig. 4 shows a theoretical PS-OPA structure with generating idler ahead of amplification, which is called “copier” structure [10-12]. The copier process is actually a process of wavelength conversion. It realizes a function of copying the information of signal wave to idler wave. The information is transmitted in two wavelengths, and finally overlapped in receiver. The advantages of this “pre-conversion” are as follows:

(1) The signal, pump and idler waves are automatically phase-locked. Any modulated signal wave can be PS-amplified, without considering the relative phase of the input waves.

(2) The signal waves with its corresponding idler waves can share a common pump wave.

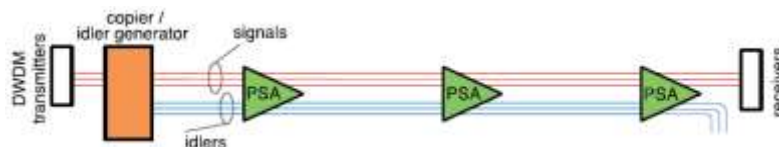


Fig. 4. The theoretical structure of copier-PS-OPA(WC+OPA) [12]

Advanced to the single wavelength transmission for information, this structure will provide a 3 dB improvement to signal wave at the receiver side [11]. If the phase sensitivity needs to be improved in PS-OPA, there should be an attenuation between the WC and OPA processes. The attenuation decreases the correlated noise generated by WC part. However, the noise de-correlation is realized usually by the

attenuation of the link. This attenuation decreases the Noise Figure (NF) of the whole link; but the transmission attenuation is inevitable. Therefore, once the fibre is longer than 50 km, without any extra attenuation, the phase sensitivity can keep increasing.

Combining the cascaded amplification and PS-OPA, an amplification with two PM-HNLF (Polarization Maintaining-) is considered. The first HNLF realize the wavelength conversion, for copy the information of signal to generated conjugated idler wave. The second HNLF amplifies the signal wave. Fig. 5 shows the theoretical structure of it.

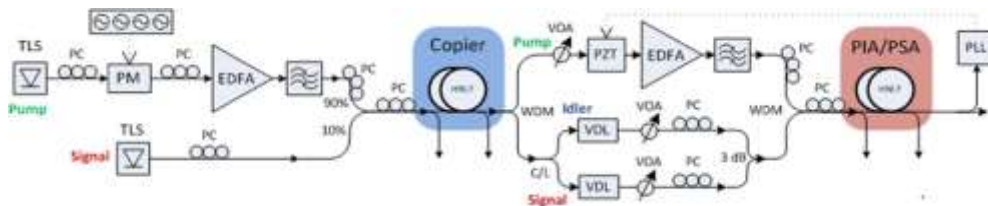


Fig. 5. The cascaded structure of WC and OPA. TLS is the tunable laser source; PM is the phase modulator; VDL is the variable delay line; VOA is the variable optical attenuation; PLL is the phase-locking loop

The first WC part realizes the copy of conjugated idler wave. The pump wave can be generated by TLS, then phase-modulated, pre-amplified by EDFA. Variable BPF with 1 nm bandwidth would filter most of the Amplified Spontaneous Emission Noise (ASE) around the wavelength of pump. The signal wave is generated by another TLS, with wavelength ranging from 1580 up to 1680 nm. After a 90/10 coupler, waves are in the first HNLF. Here the signal is copied to the idler wave. The output waves of the first HNLF are signal and conjugated idler.

The second realize the function of OPA. WDM separates the pump wave from signal and idler waves. The C+L waveband (1530-1565 nm + 1565-1625 nm) coupler separates the signal and idler waves. The attenuation discriminating the noise, pump wave is amplified again by EDFA. The Piezoelectric-Transducer (PZT) provide the phase shift [5]. This process needs a feedback from PLL, which locked the relative phase of pump and signal/idler wave, and avoiding disturbing by temperature and mechanical characteristic. For idler wave, VDL controls its temporal calibration and VOA controls its power for fear of low OSNR. The VDL and VOA keep the idler and signal waves in the same format. Finally by WDM and 3 dB coupler, all the waves are coupled into the second HNLF for PSA. The output of the PSA needs to be a feedback for eliminating the pump power.

4.2. Results and analysis

The length of the first HNLF is 90 m. Pump wavelength $\lambda_p = 1563.3$ nm, pump power $P_p = 20$ dB.m. Signal power $P_s = -25$ dB.m. The zero dispersion wavelength of HNLF $\lambda_0 = 1562.6$ nm. Higher order dispersion $\beta_3 = 4.5 \times 10^{-41}$ s³/m, $\beta_4 = 9.5 \times 10^{-56}$ s⁴/m. The nonlinear coefficient is 10 W⁻¹.km⁻¹. The simulation research was carried out in both PI- and PS-situation. Fig. 6 shows the signal gain characteristic by copying the conjugated idler wave in the first HNLF. The

maximum of PIA gain is 20 dB, while PSA is 25 dB. If 10 dB is set as the gain cutoff, the corresponding gain bandwidths are 160 nm and 170 nm. The FWHM bandwidth is around 110 nm.

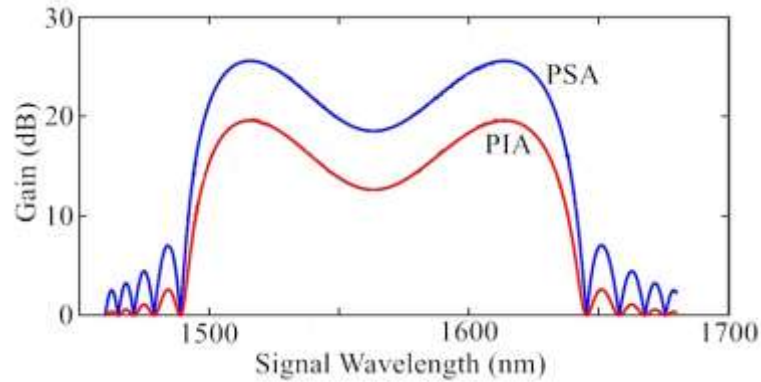


Fig. 6. Gain varies with signal wavelength in the first HNLF (WC, idler copier)

The length of the second HNLF is 45 m. As expected, in shorter HNLF the gain curve is flatter (gain fluctuation <0.2 dB of PSA, gain fluctuation <0.1 dB of PIA). The gain difference among is much less than that in the first HNLF. The peak gain of PIA and PSA decrease 14 dB and 15 dB, respectively. If 0 dB is set to be the gain cut off, the gain bandwidth is 135 nm and 150 nm, respectively. FWHM bandwidth increases to 120 nm on the contrary. Fig. 7 shows the result.

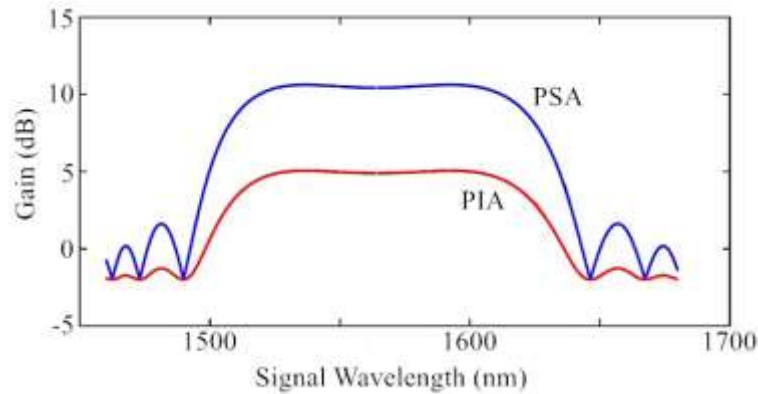


Fig. 7. Gain varies with signal wavelength in the second HNLF (OPA)

5. Conclusion

In this thesis, on demand of PM in FOPA, the QPM technique was applied in FOPA. By inserting a pump phase shifter in sections, signals amplified in corresponding HNLF or PCF would be “compensated” in phase matching. That leads to a higher gain, with flatter gain curve.

With the similar design, a cascaded structure of WC and OPA was proposed and simulated. The WC part generated idler, copied the information into idler and

pre-amplified the signal. The signal was amplified with a similar gain curve, which is not that flat at the gain peak. The OPA part amplified the signal again, to obtain a flatter gain peak.

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