Phase sensitive amplification in a periodically poled gradient lithium niobate waveguide

V V Galutskiy, S S Ivashko and E V Stroganova
Department of Optoelectronics, Kuban State University, 149, Stavropolskaya str., Krasnodar, Russia, 350040
E-mail: galutskiy17v@mail.ru

Abstract. The article presents a phase sensitive amplifier based on cascaded second harmonic generation and difference frequency generation in a waveguide in the gradient periodically poled lithium niobate. The influence of the composition gradient in periodically poled lithium niobate on phase and spectral dependence of amplification factor is described. The increase of 35% is shown in spectral range of the gradient amplifier in comparison with the gradientless one in the range of 1.55 μm. The dependence of amplification factor of the optical signal from the propagation direction in the waveguide channel in gradient PPLN is also presented.

1. Introduction
Erbium doped fiber amplifiers, semiconductor optical amplifiers and the Raman amplifiers are widely used in optical telecommunication systems [1]. These are examples of phase insensitive amplifiers. In such devices the amplification factor of the optical signal is independent of the input signal phase. Now it is useful to consider telecommunication devices in which the amplification factor can be dependent of the input phases relationship. Use of phase sensitive amplifiers, besides the abatement of noise, provides an opportunity to use them for phase and amplitude regeneration of the optical signal, dispersion compensation and suppression of modulation instability [2,3].

The considered potential circuits for the purpose of implementation of phase sensitive amplifiers must correspond to a number of requirements of modern telecommunication technologies. For example, the possibility to operate with multichannel devices that are compatible with WDM systems.

Recently waveguides in periodically poled lithium niobate (PPLN) attract considerable interest for implementation of phase sensitive amplifiers [4]. Use of cascade processes at the expense of quadratic nonlinearity allows implementing the range of interacting waves meeting telecommunication requirements.

At implementation of various optical devices on lithium niobate two types of cascade processes are considered: cascade second harmonic generation and difference frequency generation (cSHG/DFG) and cascade sum frequency generation and difference frequency generation (cSFG/DFG). Here we present the new scheme for phase sensitive amplifier on the basis of cSHG/DFG processes in PPLN waveguide.

2. Theoretical model
In this model there are three waves considered: pump, signal and idler waves. With frequency: ω_p, ω_s, ω_i. These three waves are input to the waveguide. There is fixed phases relation between these waves
at the input of the waveguide. The pump wave generates the second harmonic (2ωp), which interacts with other input waves via the process of DFG (ωi = 2ωp − ωs).

At the approach of slowly varying amplitude the equations describing cSHG/DFG can be presented, as it follows from [4]:

\[
\frac{dE_p(z)}{dz} = -\frac{a_p}{2} E_p(z) + ik_{pp} \omega_p E_{SH}^*(z) E_p^*(z) \exp(i \Delta k_{pp} z),
\]

\[
\frac{dE_{SH}(z)}{dz} = -\frac{a_{SH}}{2} E_{SH}(z) + ik_{pp} \omega_p E_p^*(z) \exp(-i \Delta k_{pp} z) + 2ik_{si} \omega_p E_s(z) E_i^*(z) \exp(i \Delta k_{si} z),
\]

\[
\frac{dE_s(z)}{dz} = -\frac{a_s}{2} E_s(z) + ik_{si} \omega_s E_{SH}^*(z) E_i^*(z) \exp(-i \Delta k_{si} z),
\]

\[
\frac{dE_i(z)}{dz} = -\frac{a_i}{2} E_i(z) + ik_{si} \omega_i E_{SH}(z) E_s^*(z) \exp(-i \Delta k_{si} z),
\]

where \(E_p\), \(E_{SH}\), \(E_s\) and \(E_i\) stand for the intensity of electric field of the pump, signal and idler waves respectively. The interacting waves propagate along the z axis of the waveguide. Coupling factors for the processes of SHG (k_{pp}) and DFG (k_{si}) are expressed by the following equations:

\[
k_{pp} = d_{eff} \left( \frac{2\mu_0}{c n_p^2 n_{SH} A_{eff}} \right)^{1/2},
\]

\[
k_{si} = d_{eff} \left( \frac{2\mu_0}{c n_i n_s n_{SH} A_{eff}} \right)^{1/2},
\]

where \(d_{eff}\), \(\mu_0\), c, \(A_{eff}\) and \(n_i\) stand for effective nonlinear coefficient, vacuum permeability, velocity of light, effective area of mode in the PPLN wave guide, refractive index for each interacting wave respectively. In the construction of the model type-0 interaction at implementation of geometry of quasi-phase adjustment was considered, in this case the effective nonlinear coefficient equals to \(2d_{33}\pi^{-1}\). Phase mismatch in the considered model equals to:

\[
\Delta k_{pp} = k_{SH} - 2k_p - \frac{2\pi}{\Lambda},
\]

\[
\Delta k_{si} = k_s + k_i - k_{SH} + \frac{2\pi}{\Lambda},
\]

where \(\Lambda\) stands for the period of grating in the PPLN waveguide, and \(k\) for the propagation vectors of the interacting waves. We will seek the solutions of the equations by means of the product of module of amplitude and phase of the interacting waves:

\[
E_j(z) = A_j(z) \exp[i \phi_j(z)].
\]

One of the important distinctions of the considered model is the presence of composition gradient in the crystal of which the PPLN with the waveguide is made. The presence of a gradient in structure of the lithium niobate may either be uncontrolled or correspond to the function set prior to the stage of crystal growing. The first option is for example a traditional method of getting crystals by means of Czochralski growth technique, where the melt composition in the crucible vary from the congruent melting point. The option with the controlled composition gradient can be obtained by means of Czochralski growth technique with fluid makeup [5]. In the model several composition gradients of lithium niobate are considered, as well as their influence on properties of the phase sensitive amplifier on the basis of PPLN with a waveguide made of them. Presence of the composition gradient in PPLN inevitably leads to a gradient of phase mismatch on length because of dependence of refraction index of the interacting waves:

\[
n_j = f(z).
\]
At estimation of amplification factor of gradient phase sensitive amplifiers, the length of pump wave amounted to 1546.0 nm, length of the signal and idler waves amounted to 1541.4 nm and 1550.6 nm respectively. The effective area of mode made 52 mum2, loss factors in the waveguide amounted to 0.35 dB/cm for the pump, signal and idler waves and 0.7 dB/cm for the second harmonica of pump. The amplification factor of a signal was calculated by means of the following formula:

$$G = \frac{[A_s(t)]^2}{[A_s(0)]^2}. \quad (11)$$

The solution of the equations (1)-(11) was made by the method of finite differences.

**Figure 1.** Composition gradients of lithium niobate (a) and corresponding signal gains (b)-(f) as the function of the initial relative pump phase for crystal length of 30 mm and pump power of 30 dBm.

**3. Results and discussion**

Figure 1(a) presents the considered composition gradients of lithium niobate for production of PPLN. The essence of all gradients is that the average value of concentration of lithium ions along the z axis is identical, i.e. on length of 30 mm or 50 mm these waveguides in gradient PPLN have identical average composition on lithium of 48.6%. The spatial distribution of the refractive index is provided
by changing the lithium content along the direction of the crystal growth axis by the Czochralski method with liquid makeup. With an uncontrolled growth process, the stoichiometric composition of lithium niobate using the Czochralski method using additional liquid charging, the composition of the crystal will change in the direction of the formation of the Li$_3$NbO$_4$ phase. The Czochralski method using additional liquid charging used makes it possible to form a composition at the crystallization front by melt-feeding of another composition (enriched or depleted in this component of the crystal). For analysis, we took crystal compositions from Li$_{0.97}$Nb$_{1.03}$O$_{3.06}$ to Li$_{0.975}$Nb$_{1.025}$O$_{3.05}$, for crystallization of which the composition of the melt Li$_{1.02}$Nb$_{0.98}$O$_{2.96}$ (T = 1253K) to Li$_{1.075}$Nb$_{0.925}$O$_{2.85}$ (T = 1245K). Thus, at a length of 30 mm, the original to create the PSA, it is necessary to ensure a change between these two compositions of the melt. Such a technological approach is achievable and experimentally presented in the work.

The desired optimal composition gradient in crystals grown by the Czochralski method with replenishment is certainly not ideal. For example, various fluctuations in the level of the melt at the crystallization front, concentration supercooling, and other undesirable factors are possible to comply with the laid composition gradient until the growth process. However, the algorithm for feeding the melt with an enriched or depleted composition provides a gradient along the direction of growth, immediately in the entire crystalline boule. And when the waveguide is formed along the growth direction (along the gradient) or the formation of domain walls with a constant step, the phase detuning gradient of interacting waves will be provided. While creating a gradient in the topology of the domain walls, there will only be a surface layer up to several millimeters thick. In this case, there are undesirable effects, for example, a malfunction in the regularity of the formation of domain walls under post-growth conditions and uneven growth of domain walls deep into the plate.

We have considered increasing gradients (increase in concentration of lithium along the z axis), as well as the gradients decreasing by the same law. Figure 1(b)-(f) presents the found results of dependence of the amplification factor of gradient PPLN on the initial phase of pump signal. The initial phases of other signals were recorded. Figure 1 shows that the maximum amplification factor is reached for PPLN with homogeneous distribution of lithium – without gradient. The presence of a gradient reduces the maximum value of amplification factor, shifting gain curves in different directions of original position for gradientless PPLN. Figure 1(b)-(d) present that the phase maxima and minima of amplification factor move symmetrically in different directions for the gradients increasing and decreasing by the same law. Figure 1(e) illustrates the phase portrait of gain curves for gradientless PPLN, and for PPLN with gradients in the form of a parabola and a reverse parabola. It is seen that phase gain curves for both parabolas coincide, except small increase in amplification factor for the parabola. Considering the phase portrait of gain curves in more detail it can be observed that, as well as in a case with gradientless PPLN, with gradient PPLN there has been amplification factor, dependent on input signal phases, observed. So, the possibility of receiving the phase sensitive amplifier of optical signals remains. Greater values of amplification factor are observed at the decreasing gradients than at the gradients increasing under the same condition (linear gradient, semi-parabola, etc.).

Curves of the maximum amplification factor of signal of the phase sensitive amplifier as a function of wavelength at the constant pump wavelength and the strength of 30 dBm are presented in figure 2. Figure 2(a) shows that the curve 1 corresponding to the maximum amplification factor of the gradientless PPLN amplifier 30 mm long has width at tuning the wavelength of 150 nm. When using PPLN with a concentration gradient in the form of parabola as the phase-sensitive amplifier the tuning range on wavelength increases by 35%. (curve 9). Figure 2(b) also shows various range of tuning on wavelength for the phase sensitive amplifier in case of the decreasing gradient in the form of a parabola (curve 8) and the gradients increasing under the same condition (curve 7). That means when using the gradient PPLN as the phase sensitive amplifier the direction of signal distribution in the waveguide – in the direction of increase or decrease of lithium concentration – will be important. This situation is illustrated most evidently in figure 3. Figure 3 demonstrates that the maximum amplification factor of the gradient PPLN converter depends on the direction of emission input in a...
waveguide. At the pump power of 30 dBm the difference in amplification factor for the increasing gradient in the form of a semi-parabola (curve 7) and the decreasing gradient in the form of a semi-parabola (curve 8) makes 10 dB.

Figure 2. Maximum PSA gain plotted as a function of the signal wavelength at input pump power of 30 dBm for the various gradients lithium niobate waveguide: (a) with gradients 1 and 9, (b) with gradients 7 and 8.

Figure 3. Maximum PSA gain as a function of the input pump power for a crystal length of 30 mm with gradients 7 and 8.

4. Conclusion
We have theoretically analysed the phase sensitive amplifier based on cascade cSHG/DFG processes in the gradient PPLN. The obtained results allow indicating the distinctive dependence of the amplification factor on the direction of distribution of optical signal in gradient PPLN. In the investigated 30 mm PPLN with gradient of lithium concentration in the form of increasing and decreasing semi-parabola the difference in the amplification factor of 10 dB has been revealed at the pump power of 30 dBm. The phase sensitive amplifier allows using this essential distinction in a controlled way. Also, during consideration of the model of a phase sensitive amplifier on the basis of gradient PPLN it was found out about the increase by 35% of width of range of tuning on wavelength for input signals in comparison with gradientless PPLN. Thus, this is the main advantage of PPLN, especially taking into account compact size and the fact that there is no need to suppress the effect of stimulated combination scattering (Brillouin scattering) as in the case with fibers. At the presence of composition gradient in the waveguide channel PPLN it is possible to get a directed phase sensitive amplifier.

Acknowledgements
The research leading to these results has received funding by the Ministry of Science and Higher Education of the Russian Federation (FZEN-2020-0022).
References
[1] Pedro J and Costa N 2018 J. Lightwave Technol. 36 1552
[2] Croussore K, Kim I, Han Y et al 2005 Opt. Express 13 3945
[3] Croussore K and Li G 2008 IEEE J. Sel. Top. Quantum Electron. 14 648
[4] Lee K J, Parmigiani F, Liu S et al 2009 Opt. Express 17 20393
[5] Galutskiy V V, Vatлина M I, Stroganova E V 2009 J. Cryst. Growth 311 1190