Phase-sensitive amplification based on gradient Er:PPLN

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Abstract. The present research focuses on the study of the phase-sensitive amplification based on periodically poled lithium niobate (PPLN) made from gradient Er doped lithium niobate. It is shown that the presence of a growing Er gradient increases the gain while maintaining phase sensitivity to the input signal.

1. Introduction

A key requirement for increasing the bandwidth of communication networks is to improve the signal-to-noise ratio (SNR) [1]. For this purpose, a number of technologies and devices for communication systems that provide a low-noise mode of amplification and regeneration of the optical signal, such as phase-sensitive amplifier (PSA), are being used and improved [2,3]. The PSA is capable of performing low-noise amplification up to 3 dB of the quantum-limited noise level, with a conventional phase-sensitive amplifier, such as an erbium fiber amplifier (EDFA) [3]. Combining the capability of a phase-sensitive amplifier with an erbium amplifier would allow amplifying the signal with feedback distributed along the length of the amplifier, which can increase the amplification efficiency and reduce the amplitude and phase noise, usual for EDFA and PSA.

Today, such laser amplifiers as erbium-activated fiber amplifiers (EDFA), optical semiconductor amplifiers (SOA), or Raman optical amplifiers are actively used. The noise level (NF) of these phase-sensitive amplifiers (PIA) cannot be improved below the quantum limit of 3 dB [3]. For phase-sensitive amplifiers (PSA), the ideal NF is 0 dB [3]. The signal-to-noise ratio (SNR) is a significant quantity that determines the maximum spectral efficiency according to the Shannon theory [1]. Therefore, the implementation of a low-noise amplifier is important for the development of high-speed optical telecommunications.

Today, most PSAs use four-wave mixing (FWM) in an optical fiber [4,5]. Due to the low nonlinearity of the fiber, a large interaction length is required for this. On the other hand, PSA based on quadratically nonlinear media can be implemented with smaller dimensions due to their higher nonlinearity, with further integration with other elements.

Recent achievements [6,7] in the technology of manufacturing gradient periodically poled lithium niobate (PPLN) and gradient-activated crystals allow us to study PSAs made from quadratically nonlinear periodically polarized lithium niobate with a gradient of distribution of the optical impurity-Er$^{3+}$ ions. In this work, we evaluate the efficiency of a phase-sensitive amplifier based on PPLN made of gradient-doped lithium niobate e Er$^{3+}$. 
2. Research method
The Er:LiNbO$_3$ crystal with a gradient distribution of Er$^{3+}$ along the length was grown by the Czochralski method using additional liquid charging [7,8] (Figure 1). The Er$^{3+}$ concentration changed from 4 at.% to 2 at.% at a length of 40 mm. Plates with a thickness of 0.5 mm were cut out of the crystal, on which a regular domain structure was applied using a complex of maskless lithography and high-voltage pollng. To study the combination of nonlinear optical and laser properties of gradient-activated Er$^{3+}$ PPLN, the distribution of spectral properties along the sample length was studied. Figure 2 shows the emission spectra measured in different parts of the crystal. To measure the emission spectra, a semiconductor laser with a radiation wavelength of 970 nm and variable power from 100 to 1000 mW was used. It can be seen from Figure 2 that when moving along the length of the plate, the initial one for fabrication PPLN, the intensity of 1.5 μm of Er$^{3+}$ luminescence increases, which indicates a gradient distribution of radiative properties.

Further, to study the effect of the concentration of Er$^{3+}$ ions on the selective properties of a phase-sensitive amplifier based on erbium-activated PPLN, a model of amplification (non-phase-sensitive) due to optical transitions of erbium in PPLN was added to the described model in [2].

As an object of research, both the crystal presented in Figure 1 and crystals with a concentration gradient of Er$^{3+}$ in the range of 0÷5 at.% are considered: with a constant concentration, with a linearly increasing and linearly decreasing. The paper considers two interrelated processes of optical amplification: parametric amplification, selective in wavelength, and broadband amplification at intraatomic Er$^{3+}$ transitions. The difference in these processes is the width of the gain loop and the value of the gain coefficient depending on the pumping power. In the considered model of a gradient parametric amplifier doped with Er$^{3+}$, the signal wavelength coincides with the wavelength of signal amplification due to intraatomic transitions of Er$^{3+}$ (for example, 1592 nm). The pump wavelength of the parametric amplifier coincides with the pump wavelength of Er$^{3+}$ (for example, 1532 nm). The idler wavelength, in this case, is 1476 nm, the wavelength of the second harmonic is 766 nm. The pump wavelength and the signal wavelength fall into the broadband gain band in the range of 1.5 μm. Considering the influence of the idler wave, it is assumed that it either does not interact with intraatomic transitions between levels $^4$I$_{13/2} \rightarrow ^4$I$_{11/2}$ Er$^{3+}$, or it is possible to use it as an additional channel for creating population inversion. This is possible in the 1.5 μm range due to a larger value of the absorption cross-section in the short-wave part than the value of the emission cross-section. Combining the possibilities of phase-independent low-threshold amplification of the optical signal due to intraatomic Er$^{3+}$ transitions...
with parametric amplification on PPLN, a competition of narrow-band phase-dependent amplification due to parametric amplification and phase-independent amplification is obtained. The distribution of the gain due to parametric gain considers the depletion of the pump. The pump depletion is also taken into account when considering the amplification due to intraatomic transitions of Er$^{3+}$. By setting a different distribution of the Er$^{3+}$ concentration along the PPLN of the amplifier, we can try to correct the fraction of emission on the signal wave and the pump wave, which will be involved in the amplification process at intraatomic transitions with the phase-dependent amplification process due to parametric interaction.

The scheme of a phase-dependent amplifier without considering the interaction of pump radiation and signal wave emission with Er$^{3+}$ ions is presented in the form of cascade generation of the second harmonic and generation of the difference frequency (cSHG/DFG) and cascade generation of the total and difference frequency (cSFG/DFG) on three waves: pump, signal and idle, with frequencies $\omega_p$, $\omega_s$, $\omega_i$. There is a fixed phase ratio between these waves at the waveguide input. The pump wave generates its second harmonic ($2\omega_p$), which interacts with other input waves through the DFG process ($\omega_i=2\omega_p-\omega_s$). In the approximation of slowly varying amplitudes, the equations describing cSHG/DFG can be represented as follows from [9]:

$$\frac{dE_p(z)}{dz} = -\frac{\alpha_p}{2}E_p(z) + i k_{pp} \omega_p E_{SH}(z) E^*_p(z) e^{i\Delta k_{pp} z},$$  \hspace{1cm} (1)

$$\frac{dE_{SH}(z)}{dz} = -\frac{\alpha_{SH}}{2}E_{SH}(z) + i k_{pp} \omega_p E^2_p(z) e^{-i\Delta k_{pp} z} + 2 i k_{si} \omega_p E_s(z) E^*_i(z) e^{i\Delta k_{si} z},$$  \hspace{1cm} (2)

$$\frac{dE_s(z)}{dz} = -\frac{\alpha_s}{2}E_s(z) + i k_{si} \omega_s E_{SH}(z) E^*_i(z) e^{-i\Delta k_{si} z},$$  \hspace{1cm} (3)

$$\frac{dE_i(z)}{dz} = -\frac{\alpha_i}{2}E_i(z) + i k_{si} \omega_i E_{SH}(z) E^*_s(z) e^{-i\Delta k_{si} z},$$  \hspace{1cm} (4)

where $E_p$, $E_{SH}$, $E_s$, and $E_i$ denote the electric field strength of the pump wave, the second harmonic of the pump wave, the signal, and idle waves, respectively. The interacting waves propagate along the $z$-axis of the waveguide. The coupling coefficients for SHG ($k_{pp}$) and DFG ($k_{si}$) processes are expressed in terms of equations [2]. When constructing the model, the type-0 interaction was considered when implementing the phase-matching geometry (quasi-synchronism), in this case, the effective nonlinear coefficient is $2d_{33}/\pi$. The phase mismatch in the considered model is:

$$\Delta k_{pp} = k_{SH} - 2k_p - 2\pi/\Lambda,$$ \hspace{1cm} (5)

$$\Delta k_{si} = k_s + k_i - k_{SH} + 2\pi/\Lambda,$$ \hspace{1cm} (6)

where $\Lambda$ is the lattice period in the PPLN waveguide, $k$ are the wave vectors of the interacting waves. We will look for solutions of equations (1-6) in the form of the product of the modulus of the amplitude and phase of the interacting waves:

$$E_j(z) = A_j(z) \exp(i\phi_j(z)).$$ \hspace{1cm} (7)

Next, the model of the gradient Er:PPLN amplifier is added to account for the interaction with transitions between levels $^4I_{13/2}$ and $^4I_{15/2}$. The system of splitting the energy levels of Er$^{3+}$ in lithium niobate was determined from the measured absorption and emission spectra (Figure 3). With this in mind, the population factors of the upper $^4I_{13/2}$ and lower $^4I_{15/2}$ laser sublevels:

$$f_a = 1 + \sum_{i=1}^7 \exp \left( -\frac{E_{1i} - E_{11}}{kT} \right)$$ \hspace{1cm} (8)

$$f_b = 1 + \sum_{i=1}^6 \exp \left( -\frac{E_{2i} - E_{21}}{kT} \right)$$ \hspace{1cm} (9)

The emission cross-sections and the absorption cross-section at the emission wavelength were determined by the Fuchtbauer-Landebug method (for example, at a wavelength of 1592 nm $\sigma_{em}=2.8*10^{-21}$ cm$^2$ (Figure 3)) from the measured emission spectra or according to the McCumber formula [10] by recalculating the absorption cross-section from the spectrum:
\[ \sigma_a(\lambda) = \sigma_e(\lambda) \exp \left( \frac{\hbar c / \lambda - E_{21}}{kT} \right). \]  

Figure 3. Absorption (red markers) and emission (blue markers) cross-section spectra.

In the considered gradient amplifier, the pump laser power was modulated in the range of 0÷35 dBm. The composition of lithium niobate for the manufacture of PPLN was considered as constant, corresponding to Li$_{0.99}$Nb$_{1.01}$O$_{3.02}$ (Li/(Li+Nb)=49.5%), and gradient in the main components. The concentration profile of Er$^{3+}$ along the PPLN was considered constant, linearly increasing from zero erbium concentration, linearly decreasing to zero erbium concentration in the range of 0÷5 at.%, the situation of the absence of a nonlinear connection between interacting waves (lithium niobate with Er$^{3+}$ without a domain structure) was also considered. This limit value of the concentration of Er$^{3+}$ in the crystal was chosen from practically realizable samples of gradient crystals that were grown of acceptable optical quality (considering the larger crystallographic ion radius of Er$^{3+}$ compared to the crystallographic radii of Li$^+$ and Nb$^{5+}$ ions). Setting the diameter of the pump spot $r_0$ at the input Er$^{3+}$:PPLN the initial pumping intensity $I_p$ was calculated. The signal intensity at the input was assumed to be at the level of 250 W/cm$^2$. The pumping rate and the population coefficient for the considered scheme of levels were assumed:

\[ W_p = \frac{I_p \lambda_p \sigma_{a,p}}{hc} ; \quad \beta = \frac{W_p \tau}{W_p \tau + 1}. \]  

Population inversion of Er$^{3+}$ energy levels

\[ n_i = N_1 \frac{W_p (\sigma_{a,p} - \sigma_{e,p}) - \sigma_{a,p}}{W_p (\sigma_{a,p} + \sigma_{e,p}) + \sigma_{a,p}}. \]  

After finding the distribution of the signal gain and absorption coefficients, respectively, in the gradient-activated Er$^{3+}$:PPLN in the absence of nonlinear optical interaction:

\[ k_{ampl} = 0.5(N_1 + n_i) \sigma_e - 0.5(N_1 - n_i) \sigma_a \]  
\[ k_a = 0.5(N_1 + n_i) \sigma_{e,p} - 0.5(N_1 - n_i) \sigma_{a,p}, \]

there was a local change in signal intensity due to signal amplification and a decrease in pumping during propagation along Er$^{3+}$:PPLN:

\[ \frac{dI_s}{dz} = k_{ampl} I_s ; \quad \frac{dI_p}{dz} = k_a I_p. \]  

Thus, the model of a gradient Er:PPLN amplifier is presented in the form of equations (1)-(4) describing the parametric phase-dependent gain and equations (15) considering the contribution to the resulting gain of the decrease in pump radiation and the decrease or increase in emission at the signal wavelength $I_s$. 
3. Results and discussion

Figure 4 shows the corresponding phase portraits for the amplifiers under consideration. These phase portraits are presented at the output of the 5 cm amplifier. The phase portraits were obtained by varying the ratio of the pump phases and the signal at the input of the gradient $\text{Er}^{3+}$:PPLN and estimating the value of the signal gain at the output of the amplifier.

The parameters of the waves involved in the interaction and the pump power and the signal wave correspond to 1532 nm — the pump wavelength, 1592 nm — the signal wavelength. The gradient of the change of $\text{Er}^{3+}$ along the length of PPLN corresponds to a constant, linearly increasing and linearly decreasing in the range of $0\div5$ at.%. It can be seen (Figure 4) that at the output of the 5 cm amplifier, the gain drops to $-20\div-40$ dB in a relatively narrow region of the phase tuning of the initial pump phase and the signal. However, there is already a difference in the level of attenuation of the non-phased signal with pumping when using PPLN with an increase from zero to 5 at.% concentration of erbium along the length of the transducer.

The maximum gain value will be reached, according to the received data, either at the end of the converter or in the middle. However, it is important to highlight the area where the gain depends most strongly on the phase difference, i.e., to highlight the area where the gain will be maximum between two attenuation peaks, in the middle between them. From the analysis of the obtained data, it follows that the distance at which the gain curve between the two attenuation peaks reaches a maximum is from 2 to 3 cm at a pump level of 30 dBm. One of the reasons is the traditional one for $\text{Er}^{3+}$ amplifiers, associated with the absorption of amplified emission when the final part of the amplifier will have a negative inversion.

Thus, for a phase-dependent amplifier, it is more efficient to use either shorter PPLN amplifiers with erbium or reduce the pumping power to 20 dBm (Figure 5). This reduction in pump power reduces the probability of photorefractive distortions in the PPLN. Both factors should have a positive impact on the functionality of amplifiers in the C-band band made of PPLN with erbium.

![Figure 4](image_url)  
**Figure 4.** Dependence of the gain on the phase difference between the signal and pumping for various $\text{Er}^{3+}$ gradients: (a) at zero erbium concentration, (b) at a constant erbium concentration, (c) at an erbium concentration increasing from zero, (d) at a decreasing erbium concentration.
Figure 5. Maximum gain for signal on $\lambda_s=1592$ nm from pump power $\lambda_p=1532$ nm for various concentration gradient: 1 – constant concentration of Er$^{3+}$; 2 – without Er$^{3+}$; 3 – constant concentration of Er$^{3+}$ without nonlinear interaction; 4 – linear increasing concentration of Er$^{3+}$

4. Conclusion
The paper considers for the first time optical signal amplifiers in the range of 1540 ÷ 1600 nm based on PPLN gradiently activated by Er$^{3+}$ ions. The considered gradients of the concentration of Er$^{3+}$ in a PPLN amplifier in the form of an increasing, decreasing, or constant concentration of Er$^{3+}$ serve as examples of phase-sensitive amplifiers and allow limiting the noise level of the signal while simultaneously amplifying it in the range of 10÷20 dB. Reducing the pumping level of the optical amplifier will favorably affect the quality of the 5 cm PPLN amplifier, since the probability of photorefractive distortions in lithium niobate decreases.

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