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Original article

Theoretical study of the EDFA optical amplifier implementation scheme improving the performance of a quantum key distribution system integrated with an WDM optical transport network

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ABSTRACT A version of an erbium doped fiber amplifier (EDFA) application scheme designed to increase the efficiency of the simultaneous quantum key distribution session and transmission of information by classical channels in a single optical fiber is explored. A theoretical study of the possibility to use EDFA in the explored way was conducted by numerical simulation methods. The mathematical model is based on the EDFA dynamics equations and the equations that determine the secure key generation rate in case of the subcarrier-wave quantum key distribution. A method for determining the optimal parameters of the scheme under study is described and the evaluation of the feasibility of using EDFA in the explored way is performed. A comparative analysis of the subcarrier-wave quantum key distribution system performance when integrated into an optical network is made in terms of the secure key generation rate for the cases when EDFA is either used or not. The results obtained demonstrate high efficiency of the scheme under study, i.e., the maximum achievable distance of the secure key distribution is increased while maintaining the efficiency of the information transmission.

KEYWORDS erbium-doped fiber amplifier, quantum key distribution, subcarrier-wave quantum key distribution

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1. Introduction

Quantum key distribution (QKD) can now be recognized as one of the most promising areas of quantum communications and cryptography in general [1, 2]. One advantage QKD features over classical encryption methods is that the security of the data transmission is based on the fundamental principles of quantum mechanics [3].

Significant interest is attracted to the possibility of introducing a QKD system into existing optical transport network based on wavelength division multiplexing (WDM) technology, practical convenience and economical benefits being the reason. Though it is a difficult task. The weak signal of a quantum channel is negatively affected by much more powerful information (classical) channels. Thus, noise signals fall into the spectral band of the quantum channel. The main reasons for their appearance include such nonlinear effects as spontaneous Raman scattering (SpRS), four-wave mixing (FWM), and linear channel crosstalk (LCXT) [4–6]. One method to minimize power of noise generated by classical channels corresponding to these effects is to reduce power of the classical channels. However, there is a reduction limit associated with the receiver's requirement for minimum classical signal power and optical signal to noise ratio (OSNR). To use signals with a power below the limit, one can use an erbium doped fiber amplifier (EDFA) placed before a receiver. In this case, the power level of the classical channels will be restored to the limiting value, however, the amplifier will generate broadband amplified spontaneous emission (ASE) noise, leading to OSNR decrease. The power of the noise exceeds the power of quantum channels significantly, making it impossible for them to propagate through the amplifier. Therefore, the quantum channel is removed from the main fiber on the receiver side before entering the amplifier in the scheme under study.

This work is devoted to the study of the EDFA application scheme using numerical simulation methods based on the EDFA dynamics equations and the equations that determine the secure key generation rate in the case of subcarrier-wave (SCW) QKD protocol [7, 8]. Optimal parameters of the EDFA are evaluated, so that to achieve minimum allowable power per channel for 40 classical channels multiplexed using WDM technology with a frequency spacing of 100 MHz. To evaluate the efficiency of the scheme under study, we compare the maximum achievable distance of SCW QKD system in the presence of classical channels with and without EDFA. The results obtained make it possible to draw conclusions about the applicability of the scheme under study and to evaluate the parameters of EDFA necessary to increase the efficiency of the QKD session, when implemented in the existing fiber optical communication line (FOCL). The evaluated parameters provide the maximum achievable distance of SCW QKD carried out simultaneously with the transmission of information via classical channels. By the expression "maximum achievable distance" we mean the maximum value of the fiber length at which the generation of a secure key is still possible, i.e. secure key generation rate is non-zero.

2. EDFA application scheme

Implementation of EDFA is one of possible ways to achieve the greatest attenuation of classical channels while maintaining the efficiency of information transmission. In order to avoid negative effect of an amplifier on the quantum channel, it is possible to use a scheme for integrating the QKD system into FOCL shown in Fig. 1.

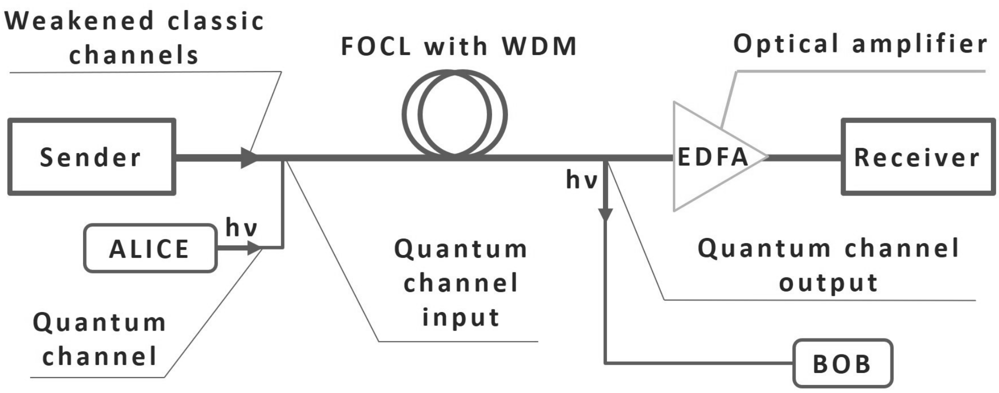

FIG. 1. Scheme of a QKD system integrated into a FOCL using an EDFA to restore the power of attenuated classical channels

On the sender side, weakened classical channels are combined with quantum channels using WDM technology and then enter the FOCL. On the receiver side, in turns, the quantum channel is diverted from the main line of the FOCL before it enters the amplifier, and then sent to the processing unit. The classical channels remaining in the FOCL are amplified with the help of EDFA and reach classical channel detectors after passing through the main demultiplexer. A similar solution was used when performing the experiment on the implementation of QKD through optical transport network in [9]. However, additionally to classical channel amplification, EDFA generates broadband noise, that is, so-called amplified spontaneous emission (ASE). It negatively affects such an information transmission efficiency parameter as OSNR. Therefore, it is necessary to carry out mathematical description of EDFA and numerical simulation of the explored circuit to determine the minimum allowable power of classical signals and the optimal parameters of the amplifier.

3. Mathematical model

3.1. Mathematical model of the EDFA

To simulate the EDFA dynamics, an ordinary nonlinear differential equation describing the relationship between the energy that enters the amplifier and the one absorbed by classical channels was used [10, 11]:

$$\frac{\partial N_2}{\partial t} = P_P\left(0,t\right)\left(1-G_P\right) + \sum_{\lambda_0}^{\lambda_n} P_S\left(0,t\right)\left(1-G_S\right) - \frac{N_2}{\tau}, \tag{1}$$

where N_2 is the number of ions at the metastable level, $P_{P(S)}\left(0,t\right)$ is the pump (signal) power value at the amplifier input, $G_{P(S)}$ is the pump (signal) gain value, and τ is the lifetime of the metastable level.

The signal power at the amplifier output $P_S\left(L,t\right)$ was determined by the formula [11]:

$$P_S\left(L,t\right) = P_S\left(0,t\right)G_S. \tag{2}$$

To calculate the channel gain G_S, the expression below was utilized [11]:

$$G_S = e^{B_S N_2 - C_S}. \tag{3}$$

In turns, the coefficients $B_{P(S)}$ and $C_{P(S)}$ used in 3 are calculated by the formula [11]:

$$B_{P(S)} = \Gamma_{P(S)} \frac{\alpha_{P(S)} + \beta_{P(S)}}{4.3429\rho A}, \tag{4}$$

$$C_{P(S)} = \Gamma_{P(S)} \frac{\alpha_{P(S)} L}{4.3429}, \tag{5}$$

where $\beta_{P(S)}$ is the absorption coefficient of the erbium-doped fiber at the pump (signal) wavelength, $\alpha_{P(S)}$ is the emission coefficient of the erbium-doped fiber for pump (signal) wavelength, ρ is the density of erbium ions, A is the cross-sectional area of the amplifying fiber core, L is the length of the amplifying fiber, $\Gamma_{P(S)}$ is the overlap integral of the doped core and optical mode for pump (signal) radiation.

The overlap integrals $\Gamma_{P(S)}$ are calculated using the formulae [12]:

$$\Gamma_{P(S)} = 1 - e^{-\frac{b^2}{w_{P(S)}{}^2}}, \tag{6}$$

where b is the radius of the erbium-doped core and $w_{P(S)}{}^2$ is the radius of the effective area of the pump mode (signal).

To estimate the ASE noise power at the wavelength of the channel under study, the formula [11] can be used:

$$P_{ASE} = 2n_{sp}h\nu\Delta\nu\left(G_S - 1\right), \tag{7}$$

where n_{sp} is the population inversion coefficient between the metastable and ground levels, h is the Planck constant, ν is the frequency of the channel under study, $\Delta\nu$ is the detector bandwidth at the channel frequency.

Finally, the population inversion coefficient can be calculated using the following formula [10, 11]:

$$n_{sp} = \frac{1}{1 - \frac{\beta_P\alpha_S}{\beta_S\alpha_P}}. \tag{8}$$

In the case of simultaneous propagation of several channels, the energy is distributed among them unevenly. To study such a process, experimental values of the absorption and emission coefficients of the fiber for different wavelengths were used (see Fig. 2).

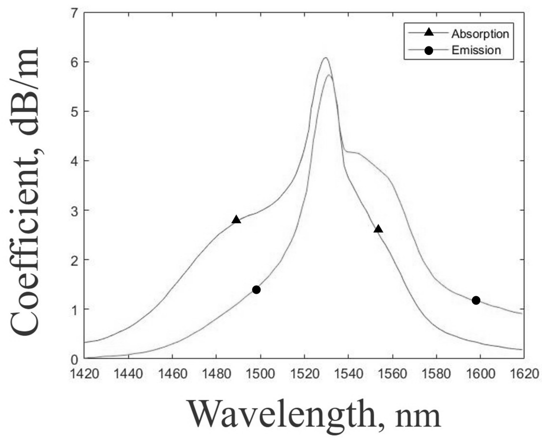

FIG. 2. Spectrum of emission (Emiss.) and absorption (Absorp.) of erbium ions doped fiber [11]

The mathematical model presented describes the dynamics of an optical amplifier in the approximation of weak information signals, which makes it possible to neglect the effect of gain saturation [13]. To describe the dynamics of EDFA with the considered parameters of the amplifying fiber under this approximation, the total power of classical channels should not exceed -2 dBm. In this work, the total power of information channels did not exceed -7 dBm, and thus, the requirement is fulfilled.

3.2. Mathematical model of noise

3.2.1. Spontaneous Raman scattering. The noise of forward spontaneous Raman scattering was determined by the formula [14]:

$$P_{\mathrm{ram,f}} = P_{\mathrm{out}}L\sum_{c=1}^{N_{\mathrm{ch}}}\rho(\lambda_{\mathrm{c}}, \lambda_{\mathrm{q}})\Delta\lambda, \tag{9}$$

where P_{out} is the output power of the fiber for one classical channel, L is the length of the optical fiber, N_{ch} is the number of information channels in the WDM system, $\rho(\lambda_{\mathrm{c}}, \lambda_{\mathrm{q}})$ is the normalized scattering cross section for the wavelengths of the information (λ_{c}) and quantum (λ_{q}) channels, $\Delta\lambda$ is the bandwidth of the filtering system quantum channels.

3.2.2. Four-wave mixing. The noise power of four-wave mixing (FWM) P_{ijk} for three pump signals featuring frequencies f_i, f_j and f_k at the new frequency $f_i + f_j - f_k$ was determined by the formula [14]:

$$P_{ijk} = \eta\gamma^2 D^2 p^2 e^{-\xi L} \frac{(1 - e^{-\xi L})^2}{9\xi^2} P_s P_l P_h, \tag{10}$$

where L is the interaction distance of the signals propagating along the fiber, D is the degeneracy parameter, ($D = 6$, $D = 3$), $P_{i(j,k)}$ and $f_{i(j,k)}$ are the input values of the power and optical frequencies of the interacting fields, respectively, γ is the third-order nonlinear coefficient, ξ is the loss factor, D_c and $dD_c/d\lambda$ are the dispersion parameters of the optical fiber, η is phase-matching efficiency, $\Delta\beta$ is the FWM parameter.

3.2.3. Linear channel crosstalk. The power leakage from the filter to the quantum channel was obtained as follows [14]:

$$P_{\mathrm{LCXT}} = P_{\mathrm{out}}\ (\mathrm{dBm}) - \mathrm{ISOL}\ (\mathrm{dB}). \tag{11}$$

where P_{out} is the output power of the fiber for one classical channel, ISOL is the inefficiency of the filter separating the quantum channel from the classical one.

3.3. Mathematical model of the secure key generation rate for a SCW QKD system

The quantum bit error rate $\mathrm{QBER}_{\mathrm{SCW}}$ was calculated by the formula [14]:

$$\mathrm{QBER}_{\mathrm{SCW}} = \frac{2\mu\tau\eta(1-\vartheta)\,(1 - cos(\delta\varphi)) + \tau\vartheta\mu_0\eta + p_{\mathrm{dark}} + p_{noise}}{4\mu\tau\eta(1-\vartheta) + 2\tau\vartheta\mu_0\eta + 2p_{\mathrm{dark}} + 2p_{\mathrm{noise}}}, \tag{12}$$

where $\eta \equiv \eta_{\mathrm{B}}\eta(L)\eta_{\mathrm{D}}$ is the value of the total optical transmission coefficient, $\mu = \mu_0 m^2$ is the average number of photons at side frequencies, m is the modulation constant, μ_0 is the average number of photons at the carrier frequency, $\tau \equiv \Delta t/T$ is the time parameter, η_{D} is the quantum detector efficiency, p_{dark} is the probability of quantum detector dark counts, p_{noise} is the probability of quantum detector noise counts, T is the time window, Δt is the gate opening time, $\eta(L) = 10^{-0.1\xi L}$ is the loss of the quantum signal in the fiber, ξ is the attenuation factor of the fiber, η_{B} is the loss in the receiver module, ϑ is the attenuation factor of the spectral filter, $\delta\phi$ is the phase shift caused by the imperfection of the equipment.

The quantum key rate K_{SCW} was calculated by the formula [14]:

$$K_{\mathrm{SCW}} = P_{\mathrm{B}}\nu_{\mathrm{S}} \left[1 - h(\mathrm{QBER}_{\mathrm{SCW}}) - h\left(\frac{1 - e^{-\mu_0 m^2}}{2}\right)\right], \tag{13}$$

where ν_{S} is the modulation frequency, $P_{\mathrm{B}} = (1 - G)/N$ is the probability of successful state detection if the receiver guesses the basis, N is the number of bases, $h(x)$ is the binary entropy function.

4. Results and discussions

The numerical simulation was performed in three stages. At the first stage, a model was developed to estimate the minimum allowable power of each of the classical channels and the length of the amplifier for a given pump power. At the second stage, the model obtained at the first stage was used to estimate the optimal pump power at which the lowest of all the minimum allowable powers of classical channels is achieved. At the third stage, the simulation of the SCW QKD session carried out simultaneously with the transmission of information via classical channels in a single optical fiber was performed. The EDFA parameters corresponding to the real ones used in transport optical networks were chosen for numerical simulation [11]. To evaluate the changes, we compare simulation results with the standard power of information channels and with their power values, optimized using the scheme under study. Let us now discuss the stages mentioned in a more detailed way.

4.1. First numerical simulation stage

The limiting value of the minimum power incident on the detector and the limiting value of the OSNR are determined by the sensitivity of the receiver. For the simulations, we used a power limiting value of -23 dBm. The lower limit of the OSNR was 9 dB. Such values correspond to the characteristics of detectors used in transport optical networks. To find the minimum allowable power value per channel, the amplification of 40 classical channels entering the amplifier at a time was simulated. The power of each information channel at the input of the amplifier varied from -15 to -25 dBm. The upper limit of the interval is the minimum required power, at which, taking into account the losses in the receiving module, no less than -23 dBm of power reaches the detector. The pump wavelength is 980 nm, which corresponds to the maximum of the absorption spectrum of erbium ions. The parameters used in our numerical simulations are given in the the Table 1

The simulation results of the gain spectrum for different signal powers are shown in Fig. 3. The simulation results of the detected power and OSNR of amplified classical channels are shown in Fig. 4.

The simulated gain exceeds 10 dB for each channel in the power range under consideration, which allows one, taking into account losses, to obtain a power at the receiver that significantly exceeds the threshold value (Fig. 4(a)). However,

TABLE 1. Parameters chosen for numerical simulations [11]

Parameter	Value	Units
ρ	$6.3 \cdot 10^{24}$	m^{-3}
A	4.52	μm^2
β_P	3.31	dB/m
α_P	0	dB/m
β_S	Corresponds Fig. 2	dB/m
α_S	Corresponds Fig. 2	dB/m

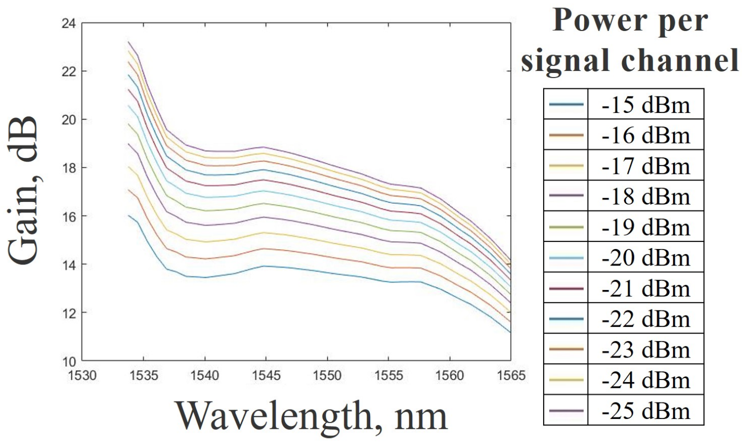

FIG. 3. Simulated gain of a classical channel versus wavelength of channel at different powers per channel

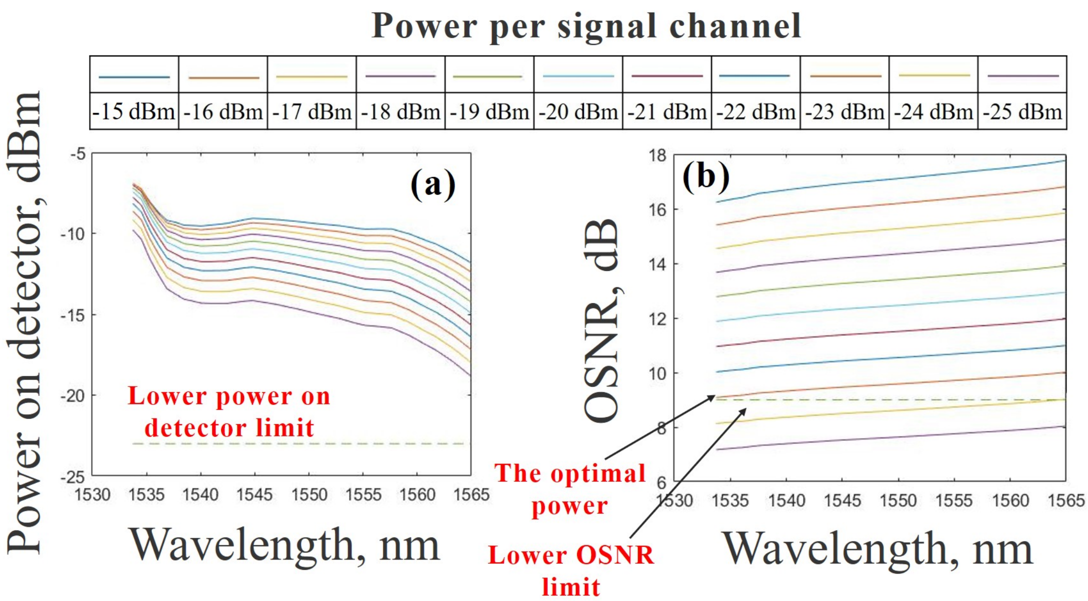

FIG. 4. Numerical simulation Results of a) Power of the amplified signal when it hits the detector versus wavelength of channel at different power per channel; b) OSNR versus wavelength of channel at different power per channel

the obtained OSNR values exceed the limit value only for powers not less than −23 dBm (Fig. 4(b)). Therefore, power of −23 dBm per channel is the minimum allowable for this system configuration and the amplifier performance.

4.2. Second numerical simulation stage

The EDFA dynamics was simulated using the above described algorithm for the pump power in the range of 10 to 40 dBm to determine the optimal pump power. Fig. 5 shows the dependence of the minimum allowable power per channel on the pump power.

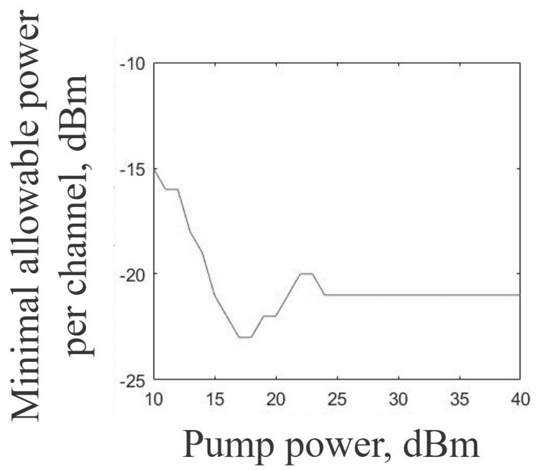

FIG. 5. Evaluated lowest allowable power per channel versus the pump power

The resulting dependence has a well-pronounced minimum in the pump power range from 17 to 18 dBm, the minimum value of power corresponding to -23 dBm per channel. We considered the behavior of characteristics depending on the pump power (Fig. 6) for the channel with the lowest OSNR (as can be seen from Fig. 4(b), this is the channel corresponding to the smallest value of the wavelength from the used range, that is 1533.7 nm) to understand the origin of the local minimum.

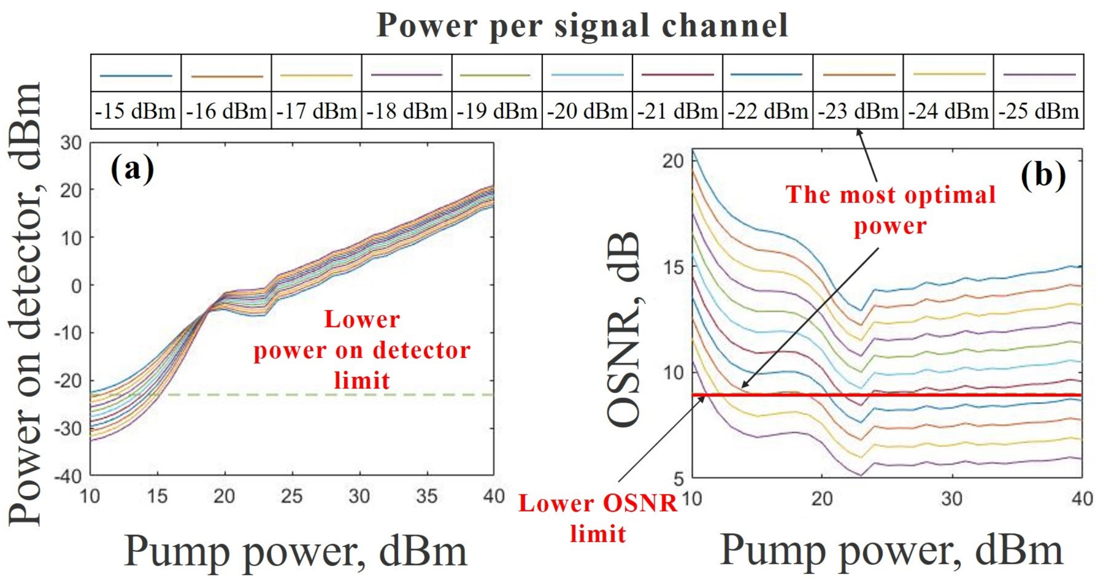

FIG. 6. Numerical simulation results for the channel at 1533.7 nm a) Power of the amplified signal when it hits the detector versus pump power at different power per channel; b) OSNR versus pump power at different power per channel

In the range from 10 to 15 dBm, the ASE noise power is much less than the signal power entering the amplifier, so the OSNR is high (Fig. 6(b)), and the minimum signal power is determined by the power hitting the detector (Fig. 6(a)). Starting from 15 dBm, the signal power at the detector begins to exceed the threshold value for almost all of the pump power values, and the minimum power value is then determined by the OSNR. Fig. 6(b) shows that in the pump power range from 17 to 18 dBm, there is a slight increase in OSNR for the channel with its minimum value, which allows one to reach the minimum allowable power of -23 dBm. This phenomenon is associated with the nonlinearity of the processes of signal amplification and ASE noise generation. At the values greater than 18 dBm, the ASE power increases. Finally, at pump powers greater than 25 dBm, the ASE power and gain per channel reach constant value, since a doped fiber has a limit of the absorbed energy. This limitation is related to the finite number of absorbing centers. This leads to the fact that the excess pump power is not absorbed by the amplifier and the OSNR reaches a constant value and determines a constant minimum allowable power of -21 dBm per information channel.

4.3. Third numerical simulation stage

To evaluate the efficiency of the scheme under study, we calculated the secure key generation rate in the case of SCW QKD protocol, based on the equations (12,13) with standard parameters (without using EDFA) and with optimized parameters (calculated reduced power of classical channels with optimal EDFA parameters). The parameters of the SCW QKD system used for simulations are: $N_{ch} = 40$, $\Delta\nu = 100$ GHz, $R_X = -23$ dBm, $\lambda_q = 1535$ nm, $\delta\lambda = 15$ nm, $ISOL = 100$ dB, $\delta\phi = 5^\circ$, $\mu_0 = 4$, $m = 0.319$, $IL = 8$ dB, $D_e = 10$ %, $p_{dark} = 10^{-6}$, $\alpha = 0.18$ dB/km, $T = 1$ ns, $L = 0 - 50$ km, $N = 2$. The results are presented in Fig. 7.

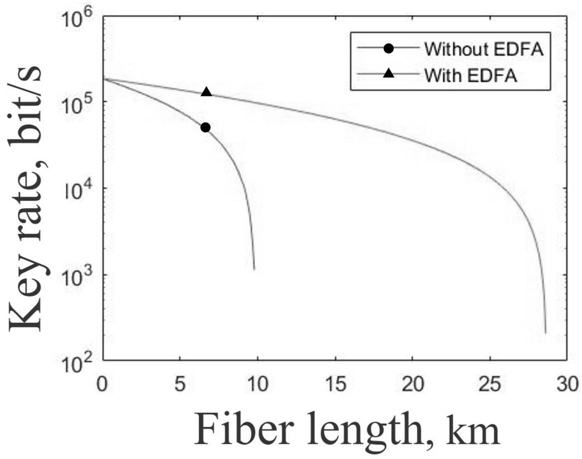

FIG. 7. Dependence of the secure key generation rate on the propagation distance for SCWQKD in the presence of classical channels with and without EDFA

The key generation rate axis is displayed on a logarithmic scale, the break in the graph corresponds to the key generation rate turning to zero. From the obtained numerical results presented in Fig. 7, it is clearly seen that, depending on whether EDFA is used or not, the distance at which successful QKD session is possible changes significantly. The use of an amplifier according to the scheme under study allows one to increase the maximum achievable distance at a non-zero key generation rate, as well as to increase the key generation rate at a fixed distance.

5. Conclusion

In this work, one of possible schemes for using EDFA to increase the performance of a QKD session was theoretically investigated. The presented scheme is quite simple to implement and has an extremely high efficiency, which was confirmed by numerical simulation. The calculated optimal parameters of the EDFA amplifier made it possible to simulate the most effective attenuation for a given number of classical channels, provided that the detector requirements are met. It was also shown, that for given characteristics of the amplifying fiber and given set of channels, the optimal pump power lies in the range from 17 dBm to 18 dBm. This is explained by the fact that the ASE power depends on the pump power and leads to the OSNR deterioration at high pump values. At lower pump powers, the OSNR is high, but there is not enough energy in the amplifier to restore the power of classical channels to the limiting value. Additionally, it was shown that for the discussed parameters the lowest power per channel to which classical channels can be attenuated is -23 dBm. In conclusion, the use of the considered scheme with these parameters, it was possible to increase the simulated maximum achievable distance of the secure key distribution session by the SCW QKD system. The presented scheme can be implemented in different ways. In the case of already existing and functioning FOCL, adding an extra amplifier to the line may not be an easy task. However, if it is possible from an engineering point of view, such a change will not lead to a deterioration in system performance, which is demonstrated in our work. Additionally, in most long-distance FOCLs, EDFA amplifiers are already used to compensate for fiber losses. In such a case the task is reduced to a mere reconfiguration of existing amplifiers, which also does not lead to a deterioration in system performance. Finally, it is also possible to design FOCL equipped with an amplifier. Such FOCLs will not only be inferior to the ones without an amplifier but will outperform them in terms of the allowable range of information transmission [15].

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