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Methods of increasing the transmission distance of a multichannel signal in FOCL

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Several ways to increase the transmission distance for multichannel signal in fiber optic communication line (FOCL) are considered. Based on the results of the numerical experiment, gain in transmission distance caused by replacing G.652-D standard fibers with G.654-C fibers was calculated. It was shown that in fiber optic communication lines with equal spans gain in transmission distance caused by fiber replacement depends on span length. The method of gain ranges' optimization for erbium amplifiers used in designed networks was proposed. Gains in transmission distance caused by using service channel multiplexors build in erbium amplifiers and budget margin reduction were evaluated.

Keywords: Fiber Optic Communication Line (FOCL), Erbium doped fiber amplifier (EDFA), FOCL optimization, DWDM, budget margin.

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Introduction

During last years we observe unprecedented rise of information scope transmitted via the fiber optical communication networks. This tendency sets out the objective of continuous rise of bandwidth capacity of fiber optical communication lines (FOCL) [1–3] equal to the product of the bandwidth capacity and the transmission distance.

The multichannel communication systems with spectral multiplexing (DWDM — Dense Wavelength Division Multiplexing) for data transmission traditionally use the wavelength band of 1529 to 1561 nm — so called C-band (Conventional band). When information signal is formed the laser optical emission is applied to the modulator, in which intensity and/or phase of the laser emission changes in accordance with the transmitted bit sequence. In DWDM systems the key factors limiting the transmission distance of the effective signal include the optical signal attenuation in the fiber, noise of amplification and reception-transmission equipment, and nonlinear effects that cause signal quality worsening as the signal power in the fiber increases. The distance can be increased by loss in fiber decreasing, optimizing characteristics of actual amplifiers available for use in actual conditions, and decreasing nonlinear degradation of the signal.

The most direct way of the transmission distance increasing is use of types of fibers with minimum attenuation in the designed networks. To date the major part of the existing FOCLs was made based on fiber of standard G.652-D SSMF (Standard Single Mode Fiber), linear losses in which amount to ~ 0.2 dB/km [4]. During lst years the fiber of standard G.654-C ULL (Ultra-Low Loss) [5] is actively used, its liner losses were reduced to ~ 0.17 dB/km. Besides, the nonlinearity coefficient in ULL fibers has lower value then in SMF fibers, this also makes them attractive for use.

Also, gains in the transmission distance can be achieved through optimal selection of amplification equipment. Most often DWDM communication systems use Erbium Doped Fiber Amplifiers (EDFA). Theoretically minimization of the noise effect on signal shall use amplifiers optimized for operation with fixed gain factor (FGA — Fixed Gain Amplifier). But under such approach the amplifier for each span shall be designed individually, which is a rather expensive solution not used in actual communication networks. Moreover, such lines do not provide the ability to compensate FOCL operation by gain adjustment. But this approach is applied in underwater communication lines [6]. State-of-art ground network frequently use EDFA with the ability to adjust the gain in some range (VGA — Variable Gain Amplifier). The noise factor of such amplifiers decreases with gain factor increasing, which leads to increase in the noise power of amplifiers in lines with short spans. Important objective is selection of the optimal ranges of gain change for the strip of used amplification equipment. At that consider that rise of number of used amplifiers in the strip results in increase of expenses for the equipment development. Besides, DWDM systems use Fiber Distributed Raman Amplifiers (DRA).

As compared to EDFA DRA have lower noise factor value, at that DRA use due to high power of pumping emission requires careful monitoring of the detachable connectors cleanness. Dust/dirt presence on the output connector of the amplifier, when DRA is used, will result with guarantee in the connector damage upon pumping emission passage through it. Besides, the price of DRA is significantly higher than that of EDFA, so DRA is usually used in addition to EDFA.

DWDM systems for interaction between the equipment installed in the intermediate points of the communication lines additional transmit data via the service channel. Most often, wavelengths of 1490 or 1510 nm are used to transmit data via the service channel. To ensure emission input/output at these wavelengths the input/output port of EDFA is provided with Wavelength Division Multiplexer (WDM). If WDM is external, then during the communication line design consider not only internal losses on WDM (~ 0.35 dB), but also losses on additional sockets required to connect the amplification equipment (~ 0.5 dB at amplifier input/output). So, the use of multiplexers build in amplifiers for emission input/output at wavelength used for service information transmission improves the transmission quality.

Traditionally, when designing FOCL various margins are considered for network operation. In paper [7] the authors recommend the margin for fiber ageing $1.6 \cdot 10^{-3}$ dB/(km·year) (~ 3.2 dB at span of 100 km and line operation life 20 years). The Russian communication operators generally require the signal quality estimation at reception considering the margin for total losses between the amplification cites per cable 3 dB for each amplification section [8]. Further in text the term budget margin will be used for the total losses between the amplification cites. Values decrease in the budget margin will result with guarantee in increase of the permitted transmission distance, at that the resistance to point losses occurrence will decrease. So, with the budget margin decreasing the communication operators shall consider that risk of FOCL accidents will increase during long-term operation.

In present paper we estimate the gain in distance due to use of new fiber type, suggest the method for selection of the optimal characteristics of the erbium amplifiers strip, evaluate gain of use of multiplexers build in amplifier for input/output of wavelength used for service information transmission, and provide results of evaluation of gain in transmission distance of non-regenerative data transmission due to budget margin decreasing. Section 1 describes the calculation model for signal quality estimation in multi-span FOCLs operating in nonlinear modes, the model is used in next Sections. Section 2 provides the estimation of gain in the transmission distance using fibers G.654-C ULL as compared to fibers G.652-D depending on the margin budget for the following signal configurations: 80 channels with rate 100 Gbit/s with modulation format DP-QPSK (80−100G DP-QPSK) in line with EDFA, 40 channels with rate 400 Gbit/s with modulation format DP-16QAM (40−400G DP-16QAM) in line with EDFA and Raman amplifiers DRA. Section 3 suggested the method for selection of the optimal gain ranges for EDFA strip. Section 4 provides the result of gain evaluation due to use of WDM build in EDFA for emission input/output at wavelength used to transmit fata via the service channel. Section 5 provides evaluation of gain in the transmission distance upon decrease in margin considered during FOCL design.

1. Calculation description

Line scheme used in calculation is shown in Fig. 1. The generated multichannel signal passes through several similar spans — fiber sections of same type and length. In intermediate cites between the spans EDFA are used to compensate losses in spans. foe each 3−5 spans the amplification cite also comprises the reconfigurable add−drop multiplexer (ROADM Reconfigurable Optical Add Drop Multiplexer) with build-in variable attenuators to level spectrum shape of the signal and additional erbium amplifier to compensate losses on ROADM. Besides, additionally during calculation in scheme a distributed Raman amplifier (DRA) can be used

When signal is spread along FOCL its quality worsens due to effect of linear (amplifier noise, chromatic and polarization-mode dispersion, filtration, etc.) and non-linear effects — self-phase modulation (SPM), cross-phase modulation (CPM), etc. The used values can be written in linear and logarithmic units. In all expressions below the uppercase letters will indicate values measured in linear units. Values measured in logarithmic units will be indicated by lowercase letters. Noises of spontaneous luminescence of amplifiers is traditionally taken into account using the linear optical signal-to-noise ratio $osnr_{\mathrm{L}}$. Effect of own noise of individual EDFA and DRA on $osnr_{\mathrm{L}}$ is considered by formula below [9]:

$$osnr_{\mathrm{L}} = p_{\mathrm{in}} - NF - h\nu\Delta\nu, \qquad (1)$$

where p_{in} — channel power of signal, NF — FOCL noise factor, $h\nu\Delta\nu$ — quantum noise power. For gain factor and noise factor calculation of counter DRA a theoretical model of counter Raman amplifier was used, the model was based on rate equations describing distribution of intensities or powers along the optical fiber [10]. The effect of the amplifier cascade can be estimated by the formula:

$$\frac{1}{OSNR_{\mathrm{L}}^{\mathrm{sum}}} = \sum_i \frac{1}{OSNR_{\mathrm{L}}^{\mathrm{i}}}. \qquad (2)$$

Degradation $\mathrm{OSNR_{NL}}$ was considered using model GNCFF (Gaussian Noise Closed Form Formula) [11]. As basic parameter for quality evaluation of DWDM-signal $OSNR$ $osnr_{\mathrm{M}}$ margin was used [12], it is evaluated by formula (2):

$$osnr_{\mathrm{M}} = osnr_{\mathrm{L}}^{\mathrm{sum}} - osnr_{\mathrm{R}}, \qquad (3)$$

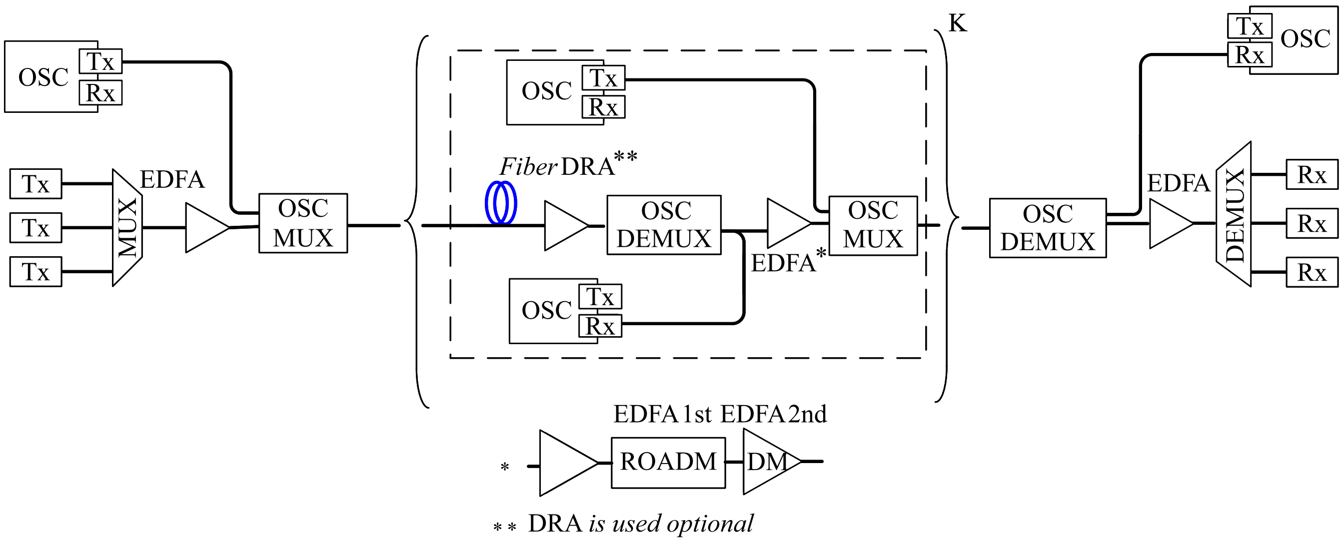

Figure 1. Scheme of calculation. Tx/Rx — signal transmitter/receiver, OSC−SFP module for data transmission via service channel, MUX/DEMUX−DWDW — multiplexer/demultiplexer, EDFA — erbium amplifier, DRA — Raman amplifier, OSC MUX/DEMUX — multiplexer/demultiplexer for emission input/output at wavelength for service information transmission, *Fiber* — fiber coil, ROADM — reconfigurable add−drop multiplexer with build in variable attenuators.

Table 1. Model configurations of FOCL

Number of FOCLs	Client load* + modulation format	Baud rate, Gbit/s	Number of channels	Channel offset, GHz	Type of fiber	Linear attenuation, dB/km	Used types of amplifiers
1	100G DP-QPSK	33	80	90 SSMF	G.652-D	0.204	EDFA
	DP-16QAM				G.654-C ULL	0.17	
2	400G DP-16QAM	69	40	100	G.652-D SSMF G.654-C ULL	0.204 0.17	EDFA + DRA

Note. * client load — transmission rate of client traffic when one channel is used in optical communication line in Gbit/s.

where $osnr_{\mathrm{R}}$ — required value of *OSNR* at reception considering imperfections of the receiving and transmitting parts (including electrical noises and quantization errors), influence of non-linear effects, penalties for chromatic dispersion, filtration [13], as well as penalty for non-optimal values of power signal at the transponder receiver.

When calculating the set configuration of FOCL we additionally optimized the total input power and pre-distortion of the signal at the entrance to the spans. The signal pre-distortion is pre-distortion of signal shape spectrum as per the linear law. EDFA with optimal gain and minimum noise factor of amplification site is installed at each cite. Depending on the calculation objective the amplifier is selected from base of FGA amplifiers (Section 2) with minimum theoretically possible noise factor or from base of VGA amplifiers with optimal gain ranges (Section 3−5). DRA pumping is calculation was performed at four wavelengths — 1425, 1435, 1455 and 1465 nm with total pumping power 1 W. Besides, losses on crosses (0.5 dB) and on WDM for add/drop channel via which the service information is transmitted (1 dB).

In calculations channels of C-band from 21 to 60 were used. List of modelled configurations is given in Table 1.

The calculation result is maximum number of spans Nmax, at which OSNR margin on work spectral band $osnr_{\mathrm{M}}$, calculated by formula (4), has value ≥ 0 dB. Using maximum number of spans $N_{\max}$ we can calculate the regeneration length $\mathrm{L_{reg}}$ equal to product of maximum number of spans and length of one span $\mathrm{L_{span}}$:

$$\mathrm{L_{reg}} = \mathrm{L_{span}} \times N_{\max}. \quad (4)$$

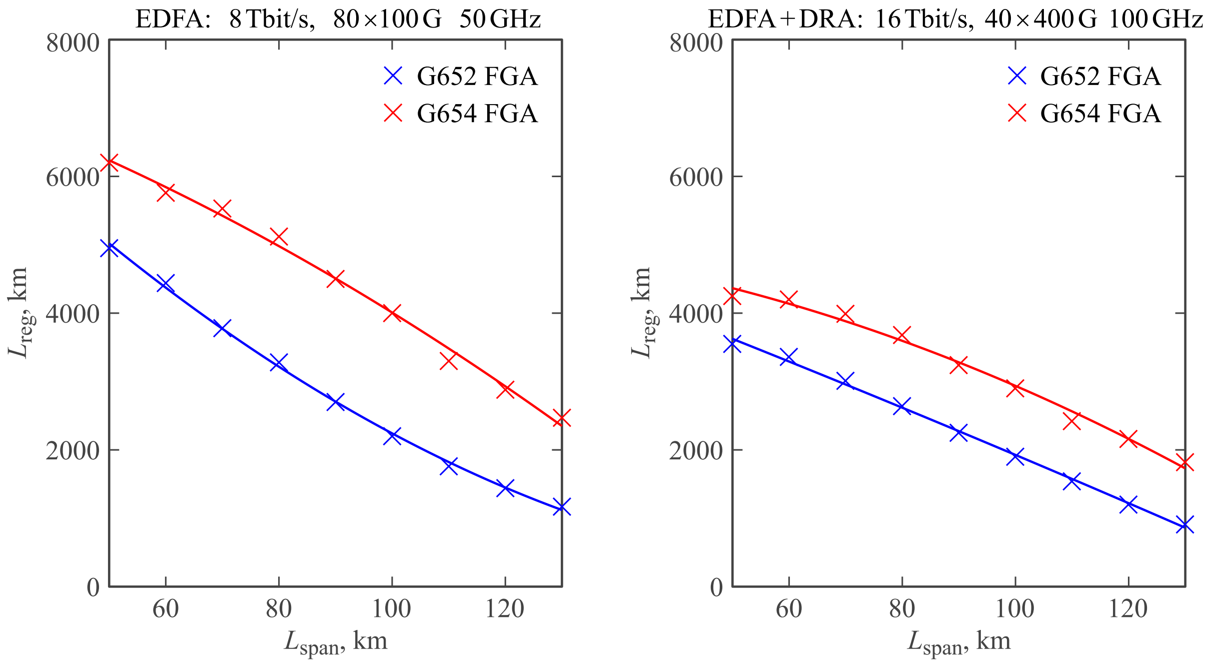

Figure 2. Regeneration length vs. span length for calculation configurations described in Table 1: *a* — FOCL 1, *b* — FOCL 2.

2. Evaluation of gain in distance when fibers G.654-C ULL are used

To evaluate the gain in use of fibers G.654-C ULL instead of fibers G.652-D SSMF a series of numerical experiments was performed relating optimization of multi-span communication lines with different types and numbers of channels for two types of channel configurations described in Table 1. During calculations on evaluation of the regeneration length the expressions (1)–(4) were used. In all calculations the length of one span varies from 50 to 130 km. Each span additionally includes the attenuation margin 3 dB. The calculations were made under the assumption that for each span length EDFA of type FGA was available with optimal gain factor and minimum noise factor for the given gain factor. For the noise factor evaluation the comparative analysis of noise factor values was made for the commercially-available FGA amplifiers from several manufacturers. Some data was taken from companys' web-sites, some data was obtained from specifications provided as per written request. At gain factors over 12 dB the minimum value of the noise factor was 5.5 dB, at lower gain factors the value of noise factor was somewhat larger. At minimum gain factor (10 dB) used in the calculation the noise factor is equal to 5.8 dB.

Fig. 2 shows the dependencies of the regeneration length on length of single span for configurations in Table 1. These dependences show that with span length increasing the regeneration length decreases monotonically.

To ensure the possibility of prompt evaluation of the non-regenerative transmission distance increasing upon the fiber replacement for each of span lengths the gain was additionally calculated for transmission distance equal to ratio of regeneration lengths when fibers G.654-C and G.652-D are used in logarithmic scale. Gain in non-regenerative transmission distance versus span length is shown in Fig. 3. The dashed line shows the difference in attenuation in one span when using different types of fibers.

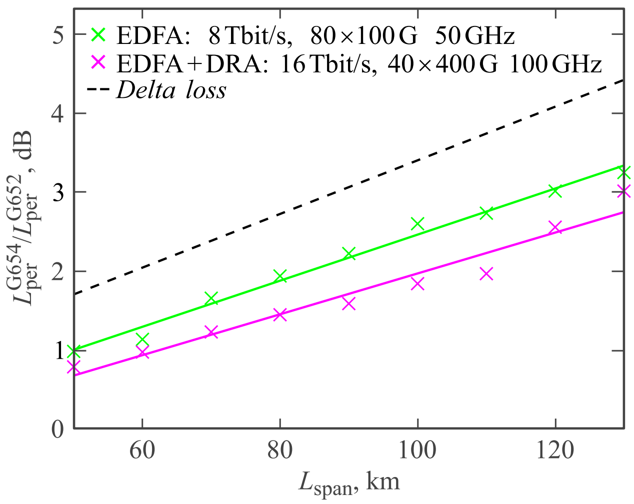

Figure 3. Gain in non-regenerative distance vs. span length using fibers G.654-C ULL instead of G.652-D SSMF for calculation configurations described in Table 1.

The gain increases uniformly with the increase in the span length. Besides, at all span lengths the gain is less than difference in attenuation. This is due to that losses difference in span at fixed span length is partially compensated by optimization of the signal power at the span entrance. When power changes the influence of both linear and non-linear effects on signal also changes. The difference in gain in regeneration length for configurations using EDFA and EDFA + DRA is determined by the fact that Raman gain factor in fibers G.654-C is lower than in fibers G.652-D. Besides, in fibers G.654-C the liner attenuation of Raman pumping is higher than in fibers G.652-D. Hence, DRA use in fibers G.654-Cis less effective than in fibers G.652-D.

3. Gain ranges optimization in erbium amplifiers

We performed the statistical analysis of attenuations introduced in one FOCL span. Fig. 4 shows distribution by budget margin and span length for sample of > 160 thousands of spans. The budget margin here is value of total losses between amplification cites that include losses in one fiber span, operation margin (typically 3 dB), losses at crosses (0.5 dB each) and losses per add/drop of service channel (1 dB each). Based on the obtained results the conclusion is made that the most probable losses in span are $\sim 19-23$ dB, and most probable span length is $\sim 60-80$ km. At that the span length can have any value in range of 0 to 410 km.

In actual ground communication lines , as it was mentioned previously, development of the optimal FGA amplifier, which compensates any attenuation of span, is extremely economically inefficient. So, DWDM equipment manufactures are faced to the objective of selection the optimal gain ranges of VGA amplifiers. The following shall be considered during selection of the gain ranges:

- Maximum gain factor of EDFA applicable for use in multichannel systems is ~ 35 dB [9];
- Gain ranges of amplifiers shall overlap such that to ensure operability keeping if required gain factor decreases by 3 dB (operation margin) for all budgets of spans;
- total number of amplifiers in the equipment strip shall be minimized;
- no critical decreasing of the transmission distance shall be observed as compared to use of optimal FGA in lines with equal spans, where only EDFA are used for amplification.

Based on the described principles it is suggested to use gain ranges in Table 2. If it is necessary to use EDFA at budget margin < 10 dB the attenuator at the amplifier output can be used.

To estimate how the regeneration length changes if optimal FGA amplifiers are replaced by VGA, described in Table 2, we performed additional series of numerical experiments on optimization of multi-span communication lines. During calculations on evaluation of the regeneration length the expressions (1)–(4) were used. Fig. 5 shows the regeneration length vs. span length for the configurations described in Table 1 if ideal FGA and amplifiers with recommended gain factors VGA with possibility of Variable Optical Attenuator (VOA) installation at the amplifier output are used. For FOCL 1 (Table 1) the regeneration length with used VGA amplifiers is close to the ideal case for both types of fibers.

Loss in L_{reg} (regeneration length) does not exceed 20% for span length of 50 to 130 km in lines with equal spans, where only EDFA are used, and for span length of 90 to 130 km in lines where EDFA+DRA are used. Decrease in number of used gain ranges leads to discontinuity in the function of the regeneration length dependence on the span length when the amplifier type changes or to decrease in range of overlapped budget margins. Noise factor in FGA amplifiers is minimal again factor, and monotonically increases with the gain factor decreasing. At that, starting from definite value of the gain factor this change is rather low (at gain factor over 10 dB the noise factor changes by less than 0.1 dB with gain factor change by 10 dB). In specific model of VGA amplifier the noise factor a;so decreases with gain factor increasing, but due to the design features such dependence significantly increases. For example, in VGA amplifier with range of gain factor readjustment from 14 to 24 dB at the gain factor 14 dB the noise factor is ~ 10 dB, and at 24 dB the noise factor is equal to 5.5 dB. As the budget margin increases, it is necessary to increase the gain factor of the used amplifiers. At some budget the type of the used amplifiers should be changed. Upon change of the used type of amplifier the noise factor changes from minimum value ~ 5.5 dB, corresponding to the maximum gain factor for the given type of amplifier, to some intermediate value of the noise factor. For example, at the budget margin 24 dB in the line the second type of amplifier will be used (Table 2) with maximum gain factor 24 dB and noise factor value ~ 5.5 dB. If third type amplifier (Table 2) is excluded, then at the budget margin 25 dB in the line the forth type amplifier will be used with minimal gain factor for the given type of amplifiers 25 dB and with noise factor value ~ 10 dB. Thus, the budget margin increasing by 1 dB will lead to a sharp increase in the noise factor and the occurrence of discontinuity in the regeneration length dependence on the budget margin. For FOCL 2 (Table 1) use of combination of EDFA from Table 2 and DRA at the amplification cite is possible only starting from span length ~ 80 km.

4. Use of build-in multiplexer of service channel

To evaluate the gain in use of add/drop multiplexer of service channel build in EDFA we performed the series of calculations for FOCL 1 described in Table 1 upon decrease in losses considered for add/drop of service channel from 1 to 0.35 dB with use of amplifiers described in Table 2. During calculations on evaluation of the regeneration length the expressions (1)–(4) were used. The decrease in losses

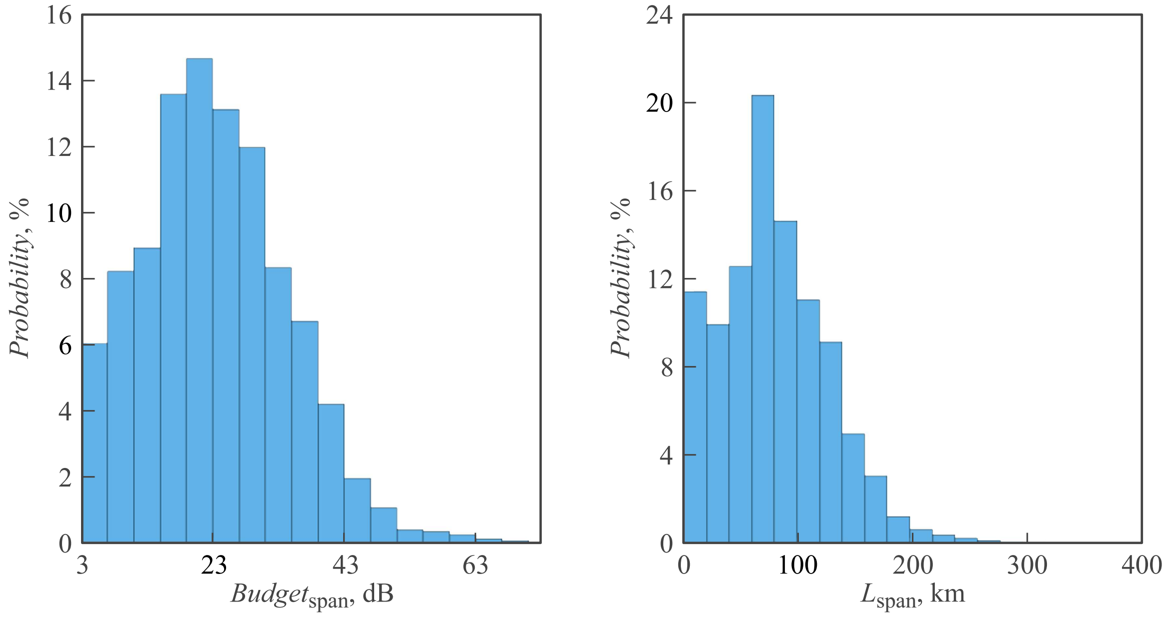

Figure 4. Distribution by losses in span for sample of > 160 thousands of spans considering operation margin, losses on crosses and losses for add/drop of service channel.

Table 2. Recommended gain ranges of EDFA

Number of amplifier type	Gain range, dB	Purpose
1	10–20	Distance maximization in lines with large number of spans with low budget
2	14–24	Noise factor minimization in lines with large number of spans with length ∼ 80 km of fiber G.652-D
3	18–28	Noise factor minimization in lines with large number of spans with length ∼ 100 km G.652-D
4	25–35	Distance maximization in lines comprising spans with large budget

is due to refusal from additional optical connectors required to connect EDFA with external WDM. The calculations were performed using VGA with the gain ranges selected in Section 4 (Table 2). Gain dependence on span length (Fig. 6) is a piecewise monotonic function. Change in nature of monotony is due to change of type of used amplifiers.

Based on calculation results the gain in the regeneration length due to use of add/drop WDM of service channel build in EDFA is 2.5–15%.

5. Budget margin decreasing

For evaluation of transmission distance dependence on the attenuation margin included in each span we performed additional series of numerical experiments for FOCL 1 configuration described in Table 1. During calculations on evaluation of the regeneration length the expressions (1)–(4) were used. The calculations were performed for three values of span length — 60, 80 and 100 km. At that the attenuation margin varied from 0 to 4 dB. The calculations were performed using VGA with the gain ranges selected in Section 4 (Table 2).

Fig. 7 shows loss in regeneration length in dB vs. margin included in each span.

With span length increasing the decrease in distance upon increase in budget margin is significant, at that the gain in distance upon decrease in the budget margin weakly depends on fiber type and span length. The obtained dependence allows us to evaluate the gain in the regeneration length with decrease in margin. So, when margin decreases from 3 to 2 dB the regeneration length increases by about 0.6 dB, i.e. by 15%.

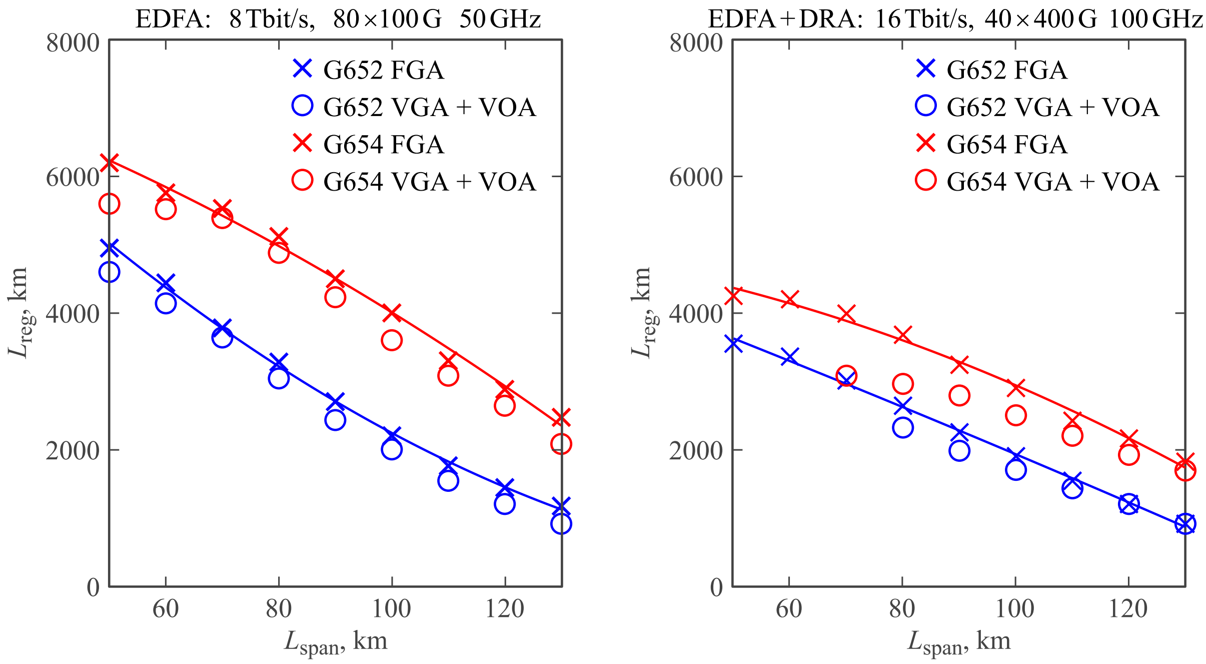

Figure 5. Regeneration length vs. span length for configurations of calculated lines described in Table 1: *a* — FOCL 1, *b* — FOCL 2 when different types of amplifiers are used.

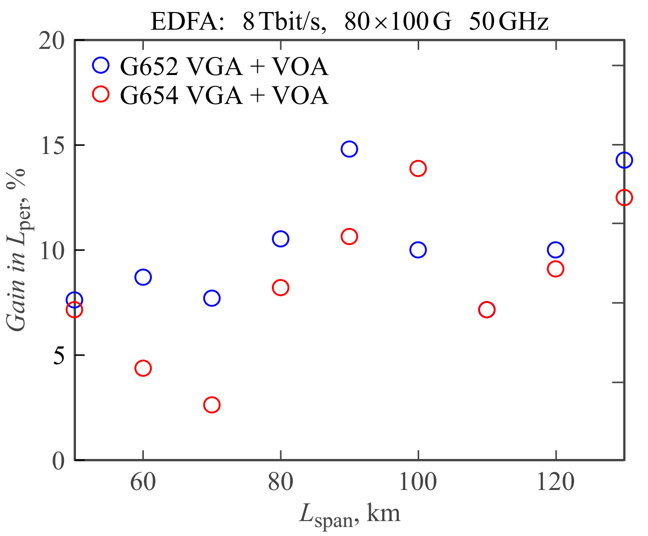

Figure 6. Gain in regeneration length vs. span length upon use of build-in add/drop multiplexers of service channel for FOCL 1 described in Table 1.

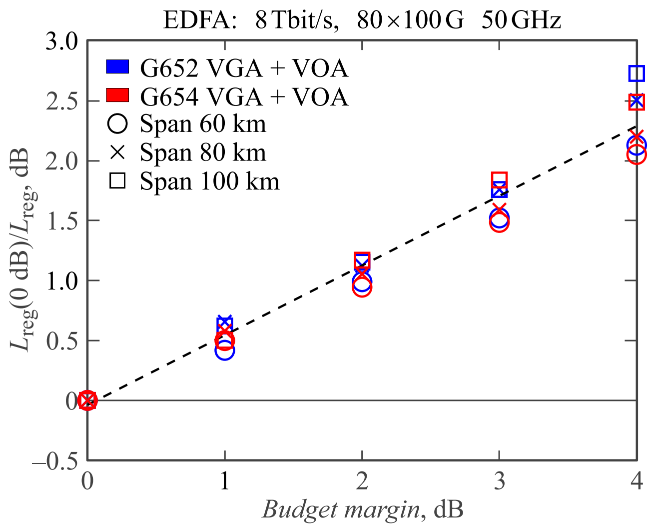

Figure 7. Loss in regeneration length vs. margin included in each span for FOCL 1 described in Table 1.

Conclusion

The paper examines various ways for the transmission distance increasing of multichannel signal in multi-span FOCLs.

Based on the numerical model of FOCL we show that replacing G.652-D SSMF fiber with G.654-C ULL fibers ensures the gain in the transmission distance which value on the logarithmic scale depends linearly on the span length. At that in lines with the distributed Raman amplifiers the gain dur to the fibers replacement is lower due to lower Raman scattering coefficient and larger attenuation of Raman pumping in G.654-C fibers. The method is suggested to optimize the gain ranges in EDFA used in actual communication lines. It is shown that use of determined gain ranges the regeneration length decreases by maximum 20% in lines with EDFA upon transfer from ideal FGA amplifiers to VGA amplifiers used in actual communication lines. It is also shown that use of build-in add/drop multiplexers of service channel ensures the transmission distance increasing by 2.5−15%. We evaluated the gain in regeneration length from reducing the budget margin included in each span during FOCL design. It is shown that decrease in budget margin from 3 to 2 dB ensures the gain in distance $\sim$ 15%.

Conflict of interest

The authors declare that they have no conflict of interest.

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