OPTIMAL FIBER PROPOSAL FOR DIGITAL SUBSEA TRANSMISSION CONSIDERING EDFA OUTPUT

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Abstract: In subsea digital coherent transmission links composed of non-dispersion-managed fibers, the major challenge is to improve the system OSNR. To be applied in such links, various fibers having low loss and large Aeff have been proposed. In this paper, we propose optimal fibers for a digital subsea system assuming a practical limit of EDFA output, based on a fiber figure-of-merit developed from a viewpoint of OSNR improvement. We reveal that fibers with the lowest possible loss will be the most preferable. As for the Aeff, there will be appropriate values of 105μm^2 to 140 μm^2, depending of the transmission distance.

1 INTRODUCTION

High capacity subsea systems based on 100G signals have been deployed applying non-dispersion-managed fibers and digital coherent technologies, in order to keep pace with radical growth of data traffic in global telecom-networks. A major challenge in such links is to improve the system OSNR. Therefore, there is a strong demand for subsea fibers to decrease the loss and nonlinearity, and various fibers have been proposed [1-3]. In addition, at SubOptic2013, we will present ultimate low loss fibers with 0.154dB/km having enlarged Aeff of 112 and 130μm^2 using a commercially manufacturable process [4].

In order to determine the appropriate fiber for a transmission system, a fiber figure-of-merit (FOM) that can predict the degree of improvement on system performance should be known. Very recently, an analytical fiber FOM [5] and Q-factors as a function of launched signal power [6] were developed using the Gaussian noise model treating nonlinear interaction (NLI) [7], which are well consistent with transmission experiments. In this paper, we modify the fiber FOM to easily predict a system performance as functions of fiber parameters and launched signal power. Then, considering EDFA-output limitation for wet-repeaters, we show that a fiber with the possible lowest loss is most preferable for subsea links. We also find that there is an optimal Aeff depending on transmission distance; ~130μm^2 for >8,000 km-reach and ~110μm^2 for the shorter one.

2 ANALITYCAL FIBER FOM

Table 1 List of Symbols

α	Transmission loss of fiber in dB/km
α_l	Transmission loss of fiber in /km
Aeff	Effective Area
L_{eff}	Effective Length = {1 - exp[-α_l L]} / α_l
γ	Nonlinear coefficient = (n_2/Aeff) × (2π/λ)
n_2	Nonlinear refractive index
D	Chromatic Dispersion
L	Fiber span length
N_S	Number of span
D_T	Transmission Distance
A_{sp_in}	Coupling loss of EDFA to fiber in linear: >1
A_{sp_out}	Coupling loss of fiber to EDFA in linear: >1
α_{sp_in}	Coupling loss of EDFA to Fiber in dB: >0
α_{sp_out}	Coupling loss of Fiber to EDFA in dB: >0
P_{ch}	Launched signal power per channel
P_{opt}	Optimized P_{ch}
P_{ch_max}	Upper limit of P_{ch}
$OSNR_{max}$	Maximum OSNR at which $P_{ch} = P_{opt}$
Q_{max}	Maximum Q-factor at which $P_{ch} = P_{opt}$
Q_R	Q-factor at which P_{ch} = R P_{opt}
FOM_R	Fiber FOM at which P_{ch} = R P_{opt}
C_1	Non-fiber parameter to determine P_{opt}
C_2	Non-fiber parameter to determine Q_{max}

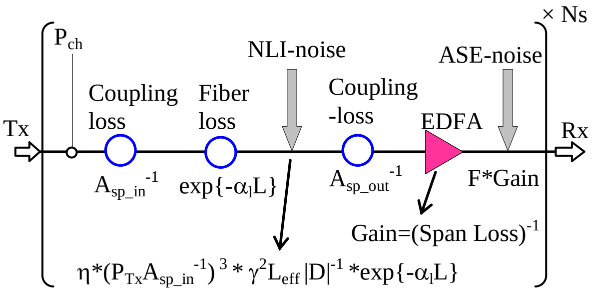

Fig. 1 Block Diagram of Considered Link.

Symbols used for this formulation are listed in Table 1. As is shown in Fig. 1, we assumed a multi-span link composed of non-dispersion-managed fibers, EDFAs and coupling losses between them. The EDFA gain at each link was assumed to completely compensate for the span loss. The $OSNR_{max}$ was developed as [5],

$$OSNR_{max} = Coeff \times \left\{\gamma^{-2} L_{eff}^{-1} \, |D| \cdot \exp[-2\alpha_l L] \cdot A_{sp\_out}^{-2}\right\}^{1/3} N_S^{-1} \quad (1).$$

Coeff is a parameter not related to fiber characteristics. Utilizing Ns= $\{D_T/L\}$, fiber FOM becomes

$$FOM[\mathrm{dB}] = -10/3 \cdot \log\left\{\gamma^2 L_{eff} \, |D|^{-1}\right\} - 2/3\alpha L + 10\log[L] - 2/3\alpha_{sp\_out} \quad (2).$$

Using the FOM, P_{opt} and Q_{max} in [6] can be expressed respectively as below,

$$P_{opt}[\mathrm{dB}] = -10/3 \cdot \log\left\{\gamma^2 L_{eff} \, |D|^{-1}\right\} + 1/3 \cdot \alpha L + \alpha_{sp\_in} + 1/3\alpha_{sp\_out} + C_1 = FOM - \{\alpha_{span}\} - 10\log[L] + C_1 \quad (3),$$

$$Q_{MAX}[\mathrm{dB}] = FOM - 10\log[D_T] + C_2 \quad (4),$$

where C_1 and C_2 are non-fiber coefficients determined by a transmission system including Back-to-Back penalty, EDFA noise-figure, baud rate, spectral efficiency, and number of channels. When a system configuration is the same, difference between FOMs of applied fibers will present a difference of the system performance (Q-factor and transmission distance). The relationship between calculated relative FOM and experimented relative transmission distance [8-11] in which values of a standard single-mode fiber (SSMF) are used as reference is shown in Fig. 2, and indeed they are well

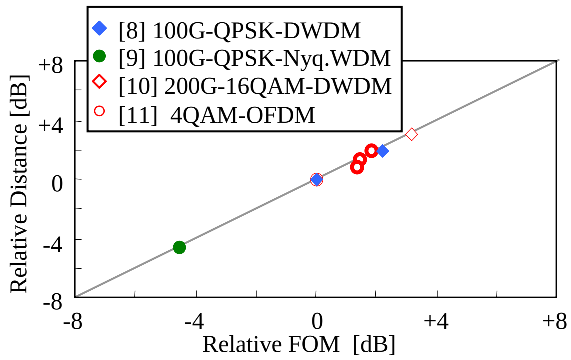

Fig. 2 Relative FOM–Relative Transmission Distance, in which SSMF's Values Are Used as Reference.

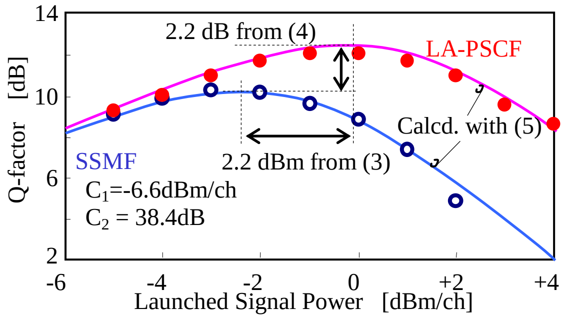

Fig. 3 Launched Signal Power – Q-factor [8].

consistent with each other. In a case that P_{ch} is not optimized, Q-factor at $P_{ch}=R \cdot P_{opt}$ of Q_R becomes

$$Q_R = Q_{MAX} + 10\log\left\{3R/(R^3+2)\right\} = FOM - 10\log[D_T] + C_2 + 10\log\left\{3R/(R^3+2)\right\} \quad (5).$$

Comparing (5) and (4), FOM_R at $P_{ch}=R \cdot P_{opt}$ can be written as

$$FOM_R = FOM + 10\log\left\{3R/(R^3+2)\right\} \quad (6).$$

100G-QPSK-DWDM experimental Q-factors as a function of P_{ch} at a distance around 4,500 km using a SSMF (open plots) and a pure-silica core fiber with α of 0.161dB/km and Aeff of 133μm^2 (LA-PSCF; solid plots) [8] are shown in Fig. 3. Calculated Q_R with (5) are shown as lines, and are in excellent accordance with experiments. Here, C_1 in (3) and C_2 in (4) were fited as 38.4dB and -6.6dBm/ch, respectively, from the transmission experiment applied SSMF.

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3 OPTIMAL FIBER CONSIDERING EDFA OUTPUT LIMITATION

In subsea wet-repeaters, a practical EDFA output is generally limited from +16 to +18dBm because of a limitation of electric power supply and broad WDM-bandwidth. In the case of 100 channels, launched power per channel in actual operation would be limited to -2dBm/ch. Laboratory experiments have been often done with unrealistic conditions, for example, the P_{opt} for LA-PSCF is around 0dBm/ch in Fig. 3.

Therefore, it will be important to discuss system performance considering a practical limit of launched signal power, P_{ch_max}. In the case for P_{ch_max} of -2dBm/ch, iso-FOM_R calculated with (6) as functions of α and Aeff at the L of 80km are shown in Fig. 4 as solid lines, along with FOM *not* considered the P_{ch_max} as dashed lines and reported fibers [1-4] as plots. In this calculation, we set P_{ch} at P_{ch_max} of -2 dBm/ch when P_{opt} is calculated to be more than -2dBm/ch using (3) with C_1 of -6.6 dBm/ch, and otherwise, $P_{ch}=P_{opt}$ (or R=1). Fibers were assumed as PSCF with D= +21ps/(nm·km) and $n_2=2.2\times10^{-20}$ m^2/W. Additionally, the coupling loss between a fiber and EDFA was assumed as the dissimilar splice loss calculated with MFD-mismatching between the applied fiber and a SSMF [1, 12]. It is clearly found from Fig. 4 that the FOM_R improvement is mainly depending on the lowering of fiber-loss and there is an optimal value in Aeff.

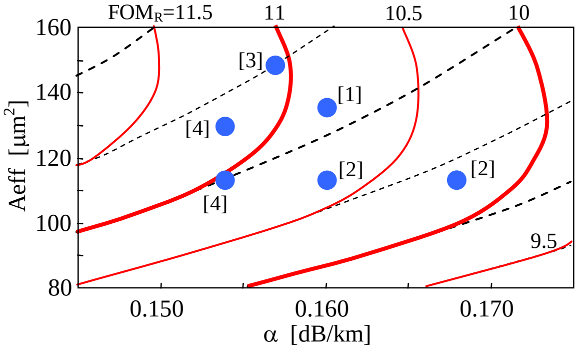

Fig. 4 Iso-FOM_R line as a function of α and Aeff at Span Length of 80km.

This is because the lower α results in the lower P_{opt} as found from (3), and therefore, P_{ch} can stay near P_{opt}. On the other hand, FOM improvement with the enlarging Aeff increases P_{opt}. However, P_{ch} cannot be higher than P_{ch_max} and FOM_R is saturated at a certain value with the larger Aeff.

Optimal Fiber Proposal requirements for subsea fibers are longer span length at a required Q-factor, and smaller Aeff if the span length is the same. The longer span length reduces the number of expensive wet-repeaters. The smaller Aeff will lead to easy handling at cabling deployment without unacceptable macro- and micro-bending loss increments.

To find an appropriate fiber for subsea link, we calculated iso-span length at Q_R of 9dB as functions of α and Aeff in Fig. 5 using (5) with C_2 of 38.4dB at transmission distances of (a) 10,000km and (b) 6,000 km. The Q_R of 9dB represents about 3dB-margin against a Q-limit of a SD-FEC. As is the case with Fig. 4, the P_{ch_max} was set at -2dBm/ch.

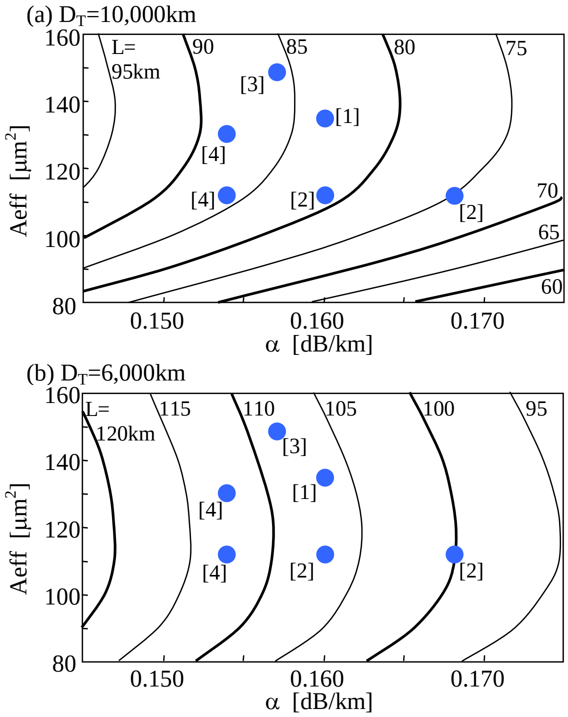

Fig. 5 Iso-Span Length line as functions of α and Aeff at Distance of (a) 10,000km and (b) 6,000km.

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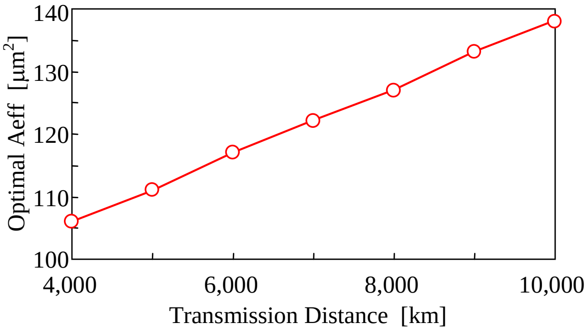

Fig. 6 Transmission Distance – Optimal Aeff at α=0.15dB/km, Q=9dB, P_{ch_max}=-2dBm/ch.

Three consequences found from Figs. 5 are as below. I) ***the possible lowest transmission loss is most preferable*** for subsea application. II) ***an optimal value of Aeff exists for maximizing the span length*** depending on the transmission distance. III) ***the optimal Aeff becomes smaller with the decreasing transmission distance***. To clarify the second and third consequences, relationship between optimal Aeff and transmission distance is shown in Fig. 6, calculated at conditions of α=0.15dB/km, Q=9dB, and P_{ch_max}=-2 dBm/ch. It is actually found that the optimal Aeff becomes smaller with the decreasing of transmission distance, and the optimal Aeff will be in the range of 120 to 140µm^2 for a distance longer than 7,000km (e.g. a transpacific link), and 105 to 120µm^2 for the shorter distance (e.g. a transatlantic link).

4 CONCLUSION

With analytically developed fiber FOM for an arbitrary launched signal power, we proposed optimal subsea fibers as ones having the lowest possible transmission loss and the optimal Aeff at a transmission distance, considering output limit of a practical EDFA for subsea operation. This proposed formulation will give a quantitative measure to find the most appropriate fiber for a certain system configuration.

The optimal Aeff alters with the system configuration including Q-factor, P_{ch_max} and signal format, but it will be safely concluded that the lowering loss always improves the system performance. From this viewpoint, newly developed PSCF with the ultimate low loss of 0.154dB/km [4] will be the most preferable subsea fiber today, we believe.

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