Low-Loss Uncoupled Two-Core Fiber for Power Efficient Practical Submarine Transmission

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Abstract: We realized 125-µm-cladding 2-core fiber with 0.162-dB/km attenuation, lowest-ever among uncoupled multi-core fibers, and effective areas of 112µm^2. It can enable 1.34-times higher capacity without increasing power consumption, compared with a state-of-the-art submarine single-mode fiber.
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1. Introduction

Spatial division multiplexing (SDM) is gaining importance in submarine transmission where limited power supply dominates the maximum available capacity because SDM enables linear scaling of capacity rather than logarithmic scaling by increasing OSNR [1,2]. On some practical assumptions, cost-optimum number of spatial channels is estimated to be ~100 (~50 core pairs) [3], which is more than 3-times larger than current practical one of a 32-fiber (16-fiber-pair) cable [4]. In order to achieve such a high number of spatial channels in submarine cable, SDM fibers with multiple spatial channels in the standard 125-µm cladding should be essential. One of most promising SDM fibers for submarine application, reported to date, is a randomly-coupled 4 core fiber that has an ultra-low 3.1 ps/√km spatial mode dispersion and an ultra-low 0.158 dB/km attenuation owing to pure silica core technology [5], which also realized 9,900 km transmission with a spectral-efficiency-distance product of 115,200 bit/s/Hz km [6]. However, it requires multiple-input-multiple-output (MIMO) digital signal processing whose techno-economic feasibility is still under study. As MIMO-less SDM fiber, Ref. [7] reported an uncoupled 7-core fiber with 0.168-dB/km low attenuation, but its cladding was as thick as 188 µm in order to isolate the cores. Ref. [8] reported an uncoupled 4-core fiber with a standard 125-µm cladding, but its attenuation was as high as 0.20 dB/km because of GeO_2-doped cores.

In this paper, we report on an uncoupled 2-core fiber (2CF) that has a 125-µm cladding and an ultra-low 0.162 dB/km attenuation, which is the lowest among uncoupled multi-core fibers. Because of this low loss and 112-µm^2 large effective areas, the present 2CF will be able to achieve 1.34-times higher transmission capacity compared with the state-of-the-art submarine single-mode single-core fiber in the current 32-fiber cables. Furthermore, the 2CF can be used assigning counter-propagating signals to each core, which alleviates crosstalk impairment and reduces granularity of fiber ownership in a submarine cable compared to co-propagating configuration.

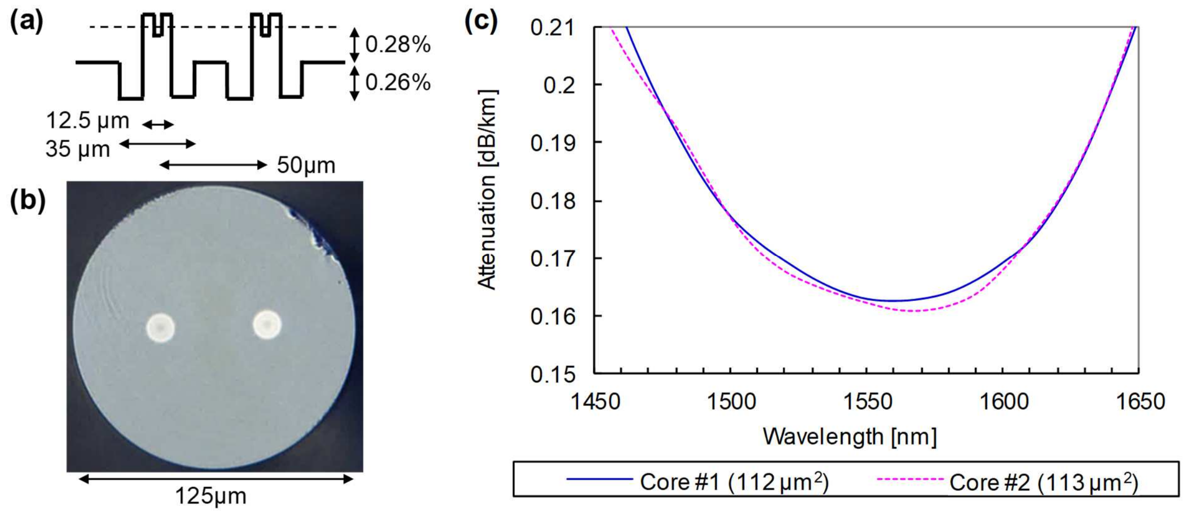

Fig. 1: (a) Schematic relative refractive index profile of the 2CF fiber where average index of the core is shown by the dashed line, (b) cross sectional image of the fabricated 2CF and (c) attenuation spectra of the two cores whose effective areas are shown in the legend.

2. Fiber design and characteristics

Figure 1 summarizes the design and fabrication results of the ultra-low loss uncoupled 2CF. As shown in Fig. 1(a), the 2CF had a relative refractive index profile composed of 2 ring-shaped cores each of which is made of a slightly F-doped center core and a pure silica ring core, whose design is similar to those of the conventional submarine fibers [9]. The cores were separated by a center-to-center pitch of 50 µm and respectively surrounded by F-doped inner claddings, and collectively surrounded by an F-doped outer cladding. The detailed values of indices and diameters, shown in the figure, were chosen to be manufacturable with a low attenuation as discussed below. We fabricated the 2CF with a standard 125 µm diameter cladding whose cross section is shown in Fig. 1(b). The attenuations of 2 cores, shown in Fig. 1(c), were as low as 0.163 and 0.162 dB/km at 1550 nm, respectively, which are record-low losses among uncoupled MCFs. The cores also had 112 and 113 μm^2 large effective areas, and those low attenuation and large area performances are comparable to some of the current submarine fibers.

The 2CF is suited to use in counter-propagating scheme where each core carries signal in opposite direction, as a fiber pair in conventional submarine cable does, because it suppresses the noise by inter-core crosstalk (XT) compared to co-propagating scheme [10,11]. In the fabricated 2CF, measured co-propagating XT (XT_{co}) was −56 dB per 100-km propagation, corresponding to a confinement loss of ~10^{-7} dB/km (excess loss due to the coupling to the other core and the coating). With this value, counter-propagating XT ($XT_{counter}$) was calculated as −80 dB per 100 km by $XT_{counter}$ [dB] = XT_{co} [dB] – 29.3 + 0.111 L_{span} [km] derived from Eqs. (1) and (5) in [11] with the assumed Rayleigh backscattering coefficient of −28.6 dB. The span length L_{span} was assumed to be 50 km. Such low XT_{co} and $XT_{counter}$ would be negligible in terms of an SNR penalty expected from XT as discussed in [7], where a much higher XT of -39.6 dB corresponds to only a 0.5 dB penalty in a system with a repeater span of 80 km. Although the cable cut-off wavelength λ_{cc} of the 2CF is 1570 nm, slightly longer than the upper bound 1530 nm of ITU-T G.654 fibers, it could be shortened by modifying cladding indices at an expense of increased crosstalk, or confinement loss. By slightly reducing the index contrast as shown in Fig. 2(a), our calculation using finite element method expects a λ_{cc} can be shortened to below 1530 nm, as shown in Fig. 2(b) along with index profile parameters of the fabricated 2CF (filled circle), with a confinement loss below 0.001 dB/km corresponding to $XT_{counter} \leq -40$ dB after 100 km, which would be still low enough to suppress the SNR penalty.

Because of suppressed XT noise, counter-propagation scheme allows weaker isolation between the cores. As a result, the present 2CF was made with a moderate ~0.54% core-cladding index contrast, as shown in Fig. 1(b), significantly lower than those of the other uncoupled MCFs, for example ~0.70% in [7]. Such a low index contrast allows to make a pure-silica-core fiber with reduced doping of lossy fluorine, and thus enables an ultra-low attenuation such as the record-low 0.162 dB/km attenuation in the present 2CF.

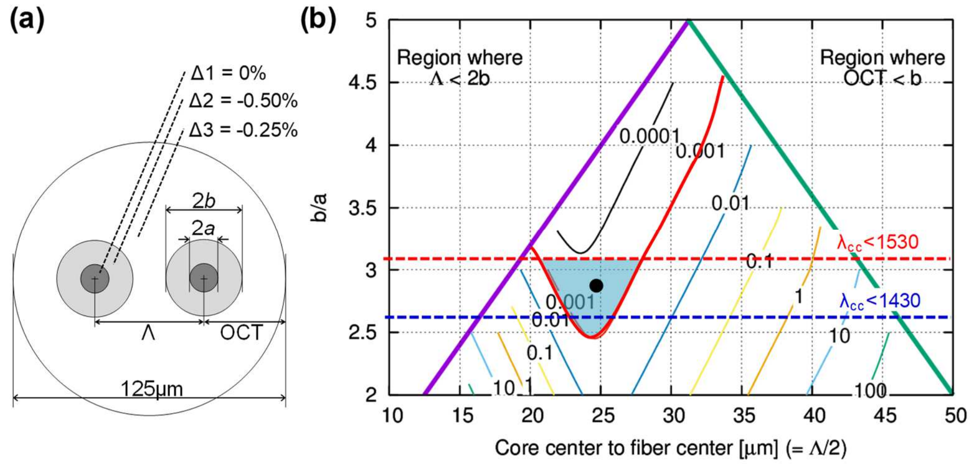

Fig. 2: (a) Schematic structure of 2-core fiber for optimization, and (b) calculated contour map of confinement losses (excess loss due to the coupling to the other core and the coating) in the optimized design of 2CF. The dot shows the values Λ/2 and *b*/*a* of the fabricated 2CF.

3. Discussion

Although the 2 cores seem a small leverage, it enables the capacity expansion under limited power and space, more effectively than improving the optical characteristics of single-mode fibers. It can be understood by calculating the capacity of an SDM submarine cable system as shown in Fig. 3 (a). The theoretical capacity is $C = 2MB \log_2(1+\text{SNR})$, where M is the number of spatial channel pairs, B is the system bandwidth, and SNR is derived from the fiber figure-of-merit theory [9,12,13]. In order to account for limitation on power supply we impose an upper bound P_{max} on total optical power P_{tot} as $P_{max} \geq P_{tot} = MN_{rep}P_{rep}$, where N_{rep} is the number of repeaters and P_{rep} is the output power of the repeaters. In the calculation, we assume a trans-pacific 11,000 km distance, 16 fiber pairs, and an upper bound of total output power +54 dBm in each direction that agrees with the assumption in a preceding study [3]. Amplifier noise figure is assumed to be 4.5 dB regardless of gain.

Figure 3 (b) shows the results of the calculated maximum capacity as a function of fiber attenuation. Span lengths are optimized for each attenuation so as to maximize the capacity under power limitation. As shown in Fig. 3(b), capacity increase from 1-core to 2-core (M = 16 to 32) was calculated to be 1.52 times if the attenuation is same, and one from 2-core to 4-core (M = 32 to 64) was limited to 1.24 times because of lower SNR. More specifically, the present 2CF with 0.162 dB/km (A) enables 1.34-times higher capacity compared to the state-of-the-art submarine fiber with 0.150 dB/km and 150 μm^2 (B). This improvement is greater than that by the Ge-doped 4-core fiber with 0.20 dB/km (C) [8], which is 1.19-times. It is also worth noting effective areas make only little difference in capacity because of limited power. So that effective areas (and index contrast) can be further optimized for lower attenuation and/or higher productivity, which should be future work.

Finally, there might be an argument that the capacity merit of a MCF system would be killed by extra losses such as those by fan-in/fan-outs (FIFOs) at the input and output of a span as in [14]. However, a bundle-type FIFO was demonstrated to have an average loss as low as 0.206 dB [15], which is comparable to a splice loss of 0.1–0.2 dB between a 1-core fiber having a 153 μm^2 Aeff and a standard SMF used in repeaters having a 80 μm^2 Aeff [16], and thus promising for implementing a 2CF system with a capacity merit as designed.

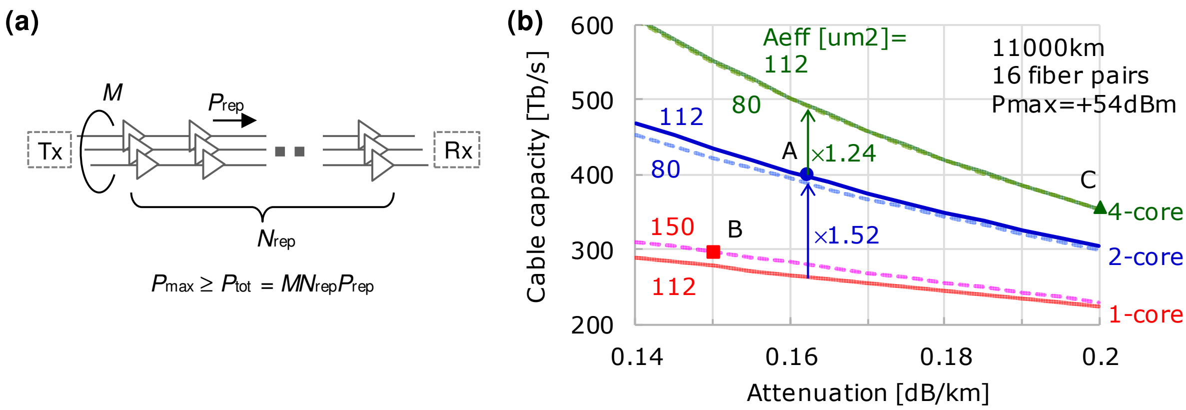

Fig. 3: (a) Schematic model of SDM cable, and (b) results of calculated maximum cable capacity for fibers having 1, 2, and 4 cores, with varied effective areas. The points A, B, and C respectively represents the present 2-core fiber, the state-of-the-art submarine fiber, and the Ge-doped 4-core fiber in [8].

4. Conclusion

We presented an uncoupled 2-core fiber with a record-low loss of 0.162 dB/km as an uncoupled MCF with index profile design considering counter propagation between cores. Fabricated 2-core MCF will have the highest transmission capacity among reported fibers with 125μm cladding and MIMO-less processing, and therefore, will be able to contribute to expansion of transmission capacity through a single submarine cable in the near future.

5. Acknowledgement

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6. References

1. P. J. Winzer, IEEE Photon. Technol. Lett. **23**(13), 851–853 (2011).
2. O. V. Sinkin *et al.*, J. Lightw. Technol **36**(2), 361–371 (2018).
3. R. Dar *et al.*, J. Lightw. Technol **36**(18), 3855–3865 (2018).
4. F. Palacios *et al.*, in *SubOptic* (2016), p. TU1A-2.
5. T. Hayashi et al., J. Lightw. Technol **35**(3), 450–457 (2017).
6. R. Ryf *et al.*, in *ECOC* 2017, p. M.2.E.1.
7. T. Hayashi *et al.*, Opt. Express **20**(26), B94–B103 (2012).
8. T. Matsui *et al.*, in *OECC2017*, 10.1109/OECC.2017.8115049.
9. Y. Yamamoto et al., J. Lightw. Technol **34**(2), 321–326 (2016).
10. T. Ito et al., in *OFC2013*, p. OTh3K.2.
11. A. Sano *et al.*, J. Lightw. Technol **32**(16), 2771–2779 (2014).
12. M. Hirano *et al.*, in *OFC* 2013, p. PDP5A.7.
13. T. Hasegawa *et al.*, Opt. Express **25**(2), 706–712 (2017).
14. J. D. Downie, J. Lightw. Technol **36**(18), 4025–4032 (2018).
15. K. Watanabe et al., in *OECC* 2012, pp. 475–476.
16. O. Levring et al., in *SubOptic* (2016), p. TU1A-5