High-Efficiency and Long-Distance Power-over-Fibre Transmission using a 125-μm Cladding Diameter 4-Core Fibre

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Abstract *By employing single-mode power-feeding over a four-core fibre with a standard 125-μm cladding diameter, power-over-fibre with 1 W class and over 10 km-long was demonstrated for the first time. Over 10 Gbit/s self-power-feeding bi-directional data communication in the single 4-core fibre is also demonstrated.*

Introduction

Power-over-fibre (PoF) is a technology that provides an optical data link with an arbitrary device (e.g., telecommunications equipment, mobile antenna, sensor, or monitor) at a remote site while supplying the electrical power to these devices by optical energy over an optical fibre, i.e. without using a metal cable or on-site power supply. The application area of PoF can be expanded if the electrical power of 1 W or more can be fed over a 10 km distance. This is because some commercially available Tx/Rx or IoT devices can operate with a maximum power consumption of 1 W or less, and the largest area of the access network that can be covered spans a 10 km radius from a central office.

Figure 1(a) and (b) respectively show the electrical feeding power and demonstrated data rate as a function of the transmission distance reported in some recent PoF experiments [1–9], where squares and circles indicate experiments utilizing multi-mode (MM) or single-mode (SM) core fibre for PoF, respectively. Generally, a photovoltaic power converter (PPC) has a larger optical-electrical conversion efficiency in the shorter wavelength region (i.e., multi-mode region in a conventional optical fibre). Figure 1(a) shows that the electrical feeding power of over 1 W was achieved using the MM-cores and 800 nm-band feed light [1–4], with a double-clad fibre exhibiting the highest electrical feeding power of 40 W [1]. A quasi-single-mode PoF utilizing a 1000 nm-band feed light also achieved an electrical feeding power of over 10 W using a 150 μm cladding diameter 7-core multi-core fibre (MCF) [5, 6]. However, the transmission distance reported in these works was limited to 1 km or less due to transmission loss. SM-core-based PoF achieved a transmission distance of several to 10 km or more by utilizing a feed light at the 1400 nm band over a conventional single-mode fibre (SMF) or MCF [7–9]. However, in these experiments, both the multiplicity factor of the electrical feeding power and the transmission distance were limited below 4 W·km because of the output optical power restriction due to stimulated Raman scattering (SRS) [10].

In this study, we demonstrate a 14.1 W·km (i.e., 1.0 W ×14.1 km) PoF by utilizing a 125 μm cladding diameter 4-core fibre with full optical compatibility by means of a conventional SMF, as indicated by the red circle in Fig. 1(a) by managing the optical reflection before it launches into the PPC. We also demonstrated the 145 Gbit/s ·km (i.e., 10.3 Gbit/s-based × 14.1 km long) self-power-feeding commercially available small form-factor pluggable+ (SFP+) module based bi-directional transmission by implementing appropriate wavelength allocation for the data and feeding light at 1310 nm and 1550 nm, respectively.

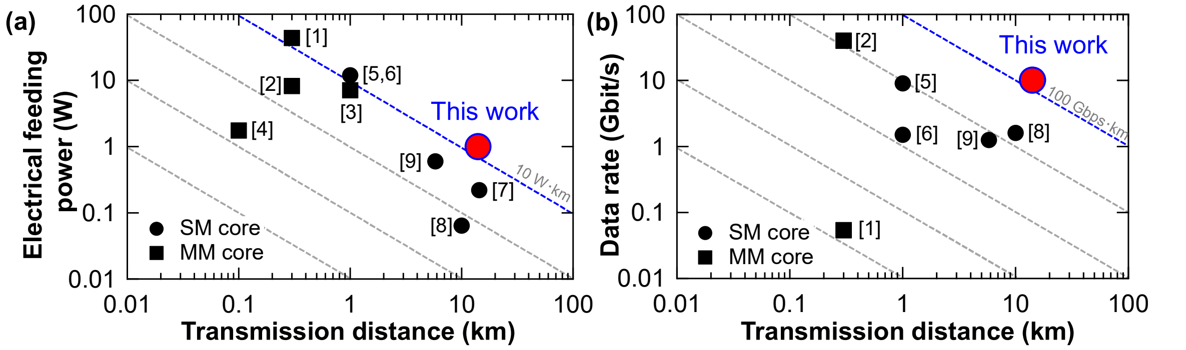


Fig. 1 Relationship between (a) electrical feeding power and transmission distance and (b) data rate and transmission distance in various PoF experiments.

4-core fibre based self-power-feeidng system

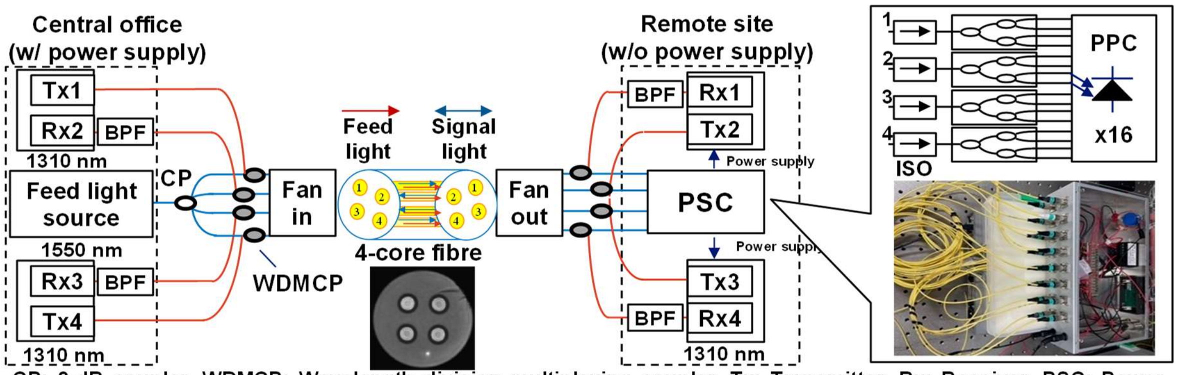
Figure 2 shows a schematic diagram of our PoF system using a 4-core fibre. The 4-core fibre has a standard 125 μm-cladding diameter and core pitch between neighbouring cores is 40 μm. Optical properties of all cores are fully compliant with a G.652.D fibre, and their attenuation coefficient and mode field diameter at 1550 nm are 0.19 dB/km and 9.8 μm, respectively. The cable cut-off wavelength was 1220 nm for the 22-m-long MCF. Although non-negligible inter-core crosstalk (XT) in an MCF causes a unique SRS property [9], we can ignore the XT-induced power fluctuation and signal degradation in a transmission several tens of kilometres long because of sufficiently low XT of 10^{-5} km^{-1}.

We selected 1550 nm as the feeding wavelength to maximize optical transmission efficiency in the single-mode regime. All four cores are utilized for delivering a power feed light with a high-power fibre laser. A pair of two cores is used for up/down data link at 1310 nm individually, which means our PoF configuration can operate two bi-directional data links in one MCF with the single-mode window. By setting the data link wavelength to be shorter than the power feeding one, we should be able to minimize the SRS-induced signal-to-noise ratio degradation in the data signal. We utilized one or two pairs of commercially available SFP+ modules for data communication with the data rate of 10.3 Gbit/s. Power feeding and optical communication lights were launched into or detected from a 4-core fibre using a WDM coupler and one pair of MCF fan-in/fan-out devices. An SFP+ module on the remote site was operated with a fed electrical power via a power supply circuit (PSC) to connect the 4-core fibre to the PPC, as shown in inset at the right-hand side. The feeding optical power received at the remote site was divided into 16 ports using a cascaded 3 dB-coupler, since the maximum input optical power to the PPCs was limited to below 600 mW.

Experimental results

Figure 3(a) shows the measured maximum optical output power as a function of the transmission distance. Here, an 18 W optical feed light was guided into 4 cores in the MCF (i.e., 4.5 W/core) at the input end as a maximum, and the maximum output power was restricted by an SRS depending on the transmission distance. It has been suggested that reflections at the fibre end-face can affect the SRS behaviour [11], and then we investigated the impact of light reflection at the PSC on the SRS by utilizing isolators. Circles and squares in the figure indicate results obtained with and without the isolators, respectively. As we can see in Fig. 3(a), an optical output power of more than 3.4 W was obtained for transmission up to 14.1 km long. It is also clear that the maximum optical output power was improved by using the isolators. The return loss with and without isolators was 50 dB and 13 dB, respectively, as measured by the OTDR method [12]. Although the optical output power improvement depends on the transmission distance, we confirmed a 40% higher optical output power as a maximum by suppressing reflection. It can be expected that the suppression of reflected light at the PSC reduces the amount of Stokes light re-coupled to the self and other cores, thereby maximizing the potential of the 4-core fibre. We should point out here that angled cleaving cannot be utilized because it degrades the coupling efficiency of the PPCs. Thus, we confirmed that an optical output power almost four times higher than the theoretical SRS threshold [10] in a conventional SMF can be obtained by using our 4-core fibre with managed optical reflection at the PSC.

Figure 3(b) shows the transmission distance dependence of the electrical feeding power that was converted from the feed light over the MCF. The optical-electrical conversion efficiencies of the PPCs were individually evaluated as 22–28% at 1550 nm and depended on the input optical power to the PPC.



CP: 3-dB coupler, WDMCP: Wavelength division multiplexing coupler, Tx: Transmitter, Rx: Receiver, PSC: Power supply circuit, PPC: Photovoltaic power converter, BPF: Band-pass filter, ISO: Isolator

Fig. 2 Schematic diagram of PoF system using 4-core fibre and configuration of power supply circuit (PSC).

These findings confirm that the measured and estimated results are in good agreement. Since the maximum power consumption of the 10G SFP+ module in our setup is generally 1 W per unit or less, Fig. 3(b) also confirms that one and two bi-directional data links should be able to support transmission distances up to 14.1 km and 6.4 km, respectively. These results demonstrate that our proposed PoF configuration achieves the highest electrical feeding power and transmission distance multiplicity factor of more than 14.1 W·km. Since we utilized a conventional 125-μm cladding diameter, an electrical feeding power factor in a unit area of more than 1.15 $\times 10^{-3}$ W·km/μm^2 could be achieved. This figure of merit represents a more than 1.7 times improvement compared to the previous reports [1–9].

Thus, our 4-core fibre with sufficiently low XT and full SMF compatibility makes it possible to construct a PoF with higher spatial utilization efficiency. Moreover, the ratio of output electrical power to input optical power reached 0.12, which is 10% higher than that with an SMF over 10 km [7], indicating that the SM-based PoF with 1550-nm feeding light has a better optical-to-electrical conversion efficiency.

Finally, we evaluated the bi-directional data link performance in our PoF configuration. Figure 4 shows the measured BER performance as a function of the received power, which was varied by using a variable optical attenuator inserted before a receiver of SFP+ (Rx). We also utilized a band-pass filter (BPF) with a bandwidth of 15 nm to reduce the noise contribution caused by the feed light. A pseudo random binary sequence (PRBS) 2^{31}-1 data signal of 10.3 Gbit/s was used. Circles indicate the BER under a back-to-back condition. Squares and triangles show the BER performances obtained when we constructed 14.1 km-long one-pair and 6.0 km-long two-pair bi-directional data links within one fibre, respectively, which correspond to data rate and transmission distance multiplicity factor of 145.2 and 123.6 Gbit/s ·km, respectively. We confirmed no error floor at BER>10^{-13} in both configurations. We should point out that there is a 2–3 dB power penalty compared to the back-to-back conditions, which is presumably caused by the increased noise level due to the much higher optical power of the feeding light compared to the optical signals. These results demonstrate that our PoF configuration enables the optically self-powered-feeding bi-directional data communication of more than 100 Gbit/s ·km.

Conclusion

We successfully demonstrated the simultaneous offering electric power feeding and data transmission using a 4-core fibre with a standard cladding diameter of 125 μm. By managing the reflection in our proposed PoF system, we achieved a power feeding performance of 14.1 W·km and improved the SRS threshold of the 4-core fibre by up to 40% compared with non-managed reflection, thereby maximizing power feeding performance. Additionally, we achieved a multiplicity factor of 145 Gbit/s·km for data rate and transmission distance with bi-directional transmission using self-power-feeding. The proposed based PoF configuration is expected to expand the application area of PoF transmission systems by means of supplying 1 W-electric power over 10 km or longer distance.

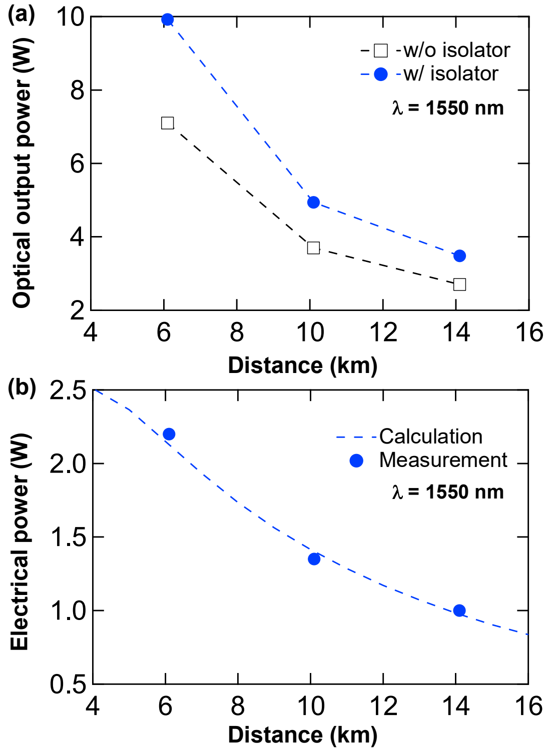


Fig. 3 (a) Relationship between optical output power and distance of 4-core fibre with and without isolators. (b) Calculation and measurement results of electrical power vs. transmission distance for PoF system.

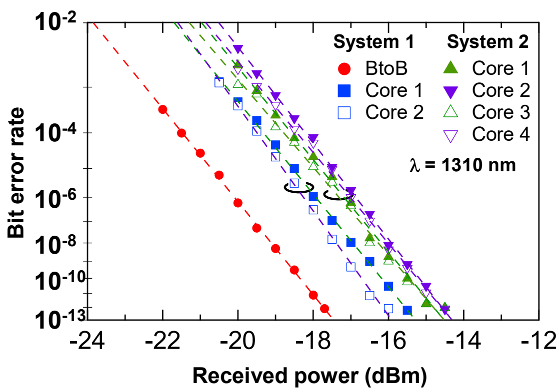


Fig. 4 Measured BER performance of 14.1-km-long one-pair and 6.0-km-long two-pair bi-directional data links as a function of received power.

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