Power-Over-Fiber Using Double-Clad Fibers

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(Invited Paper)

***Abstract*—Power-over-fiber (PWoF) is an attractive technology for transmitting power utilizing optical fibers. Because optical fibers are nonconductive power lines, and can transmit data signals simultaneously, PWoF enables us to provide usages that are not feasible with conventional electric power supply systems using copper wires. This study presents an overview of PWoF using various types of optical fibers, and introduces a practical application for powering remote antenna units (RAUs) in mobile communications. To power a RAU, the author's group has worked on PWoF using double-clad fibers, which comprise a single-mode core and an inner cladding that surrounds the core. The core structure is more suitable for simultaneous high-speed data signals and high-power feed light transmission than other optical fibers. To demonstrate the feasibility, the experimental demonstrations of the authors' group are introduced in detail. In addition, the latest performance comparison of PWoF reported so far is presented, and future prospects are described.**

***Index Terms*—Double-clad fiber (DCF), mobile communications, optical power transmission, photovoltaic power converter (PPC), power-over-fiber (PWoF), radio-over-fiber (RoF), remote antenna unit (RAU).**

I. Introduction

With the rapid development of mobile communication technologies, radio-over-fiber (RoF) has become essential for achieving higher capacity data communications [1]−[3]. It is desirable for remote antenna units (RAUs) to provide wireless communication with mobile terminals over optical fibers in all types of locations, and thus RAUs require operational technologies that can be adapted to various installation environments. In addition, as the carrier frequency of radio-frequency signals increases and cell size decreases, more RAUs with simpler installation techniques will be required.

Electric power is always required for communication. In main communication facilities such as network nodes and central offices (COs), it is relatively easy to utilize commercial power supply facilities because they are installed in office areas and densely populated areas where infrastructure facilities are well developed [4], [5]. However, RAUs required distributed installation over a wide area, which makes it difficult to utilize commercial power supply facilities in some installation environments. In addition, if the area where the RAU is installed has a power failure, the mobile communication service will also stop. Therefore, the installation environment and the availability of RAUs depend on the power supply facilities in the neighborhood. This challenge will become an important issue in future mobile communications, when more RAUs will be required in various installation environments.

To address this limitation, the author's group has worked on power-over-fiber (PWoF) for powering RAUs in RoF networks [6]−[13]. If mobile data can be transmitted with electric power to drive a RAU using an optical fiber, the installation of the RAU will be much easier because there is no need to construct electric power supply facilities and install electric power lines. Furthermore, by taking advantage of the characteristics of optical fibers, which are not determined in conventional copper wires, it will be possible to provide an attractive power supply system that can respond more flexibly to the installation environment of RAUs.

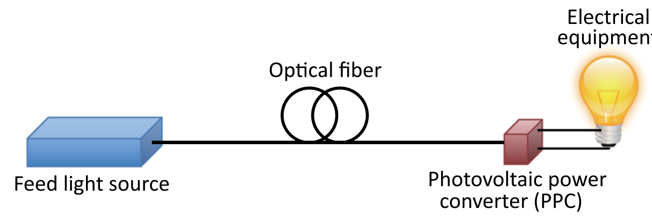

Fig. 1. Basic configuration of PWoF.

Fig. 1 illustrates the basic configuration of PWoF. There are three key components: a feed light source, an optical fiber, and a photovoltaic power converter (PPC). The feed light source is a high-power laser for delivering optical power, and the generated feed light is injected into an optical fiber. After fiber transmission, a PPC converts the optical power into electric power to drive any electrical equipment, such as communication facilities. Compared to conventional copper wires, optical fibers are lightweight, resource-saving, and corrosion-resistant. It is also advantageous for power supply systems in water because there is no fear of electric leakage. The most important feature of optical fiber is that it does not conduct electricity; hence, as a power line for RAUs, it is highly resistant to electromagnetic interference, and plays a role in blocking reverse currents such as those caused by lightning strikes on the antenna of RAUs.

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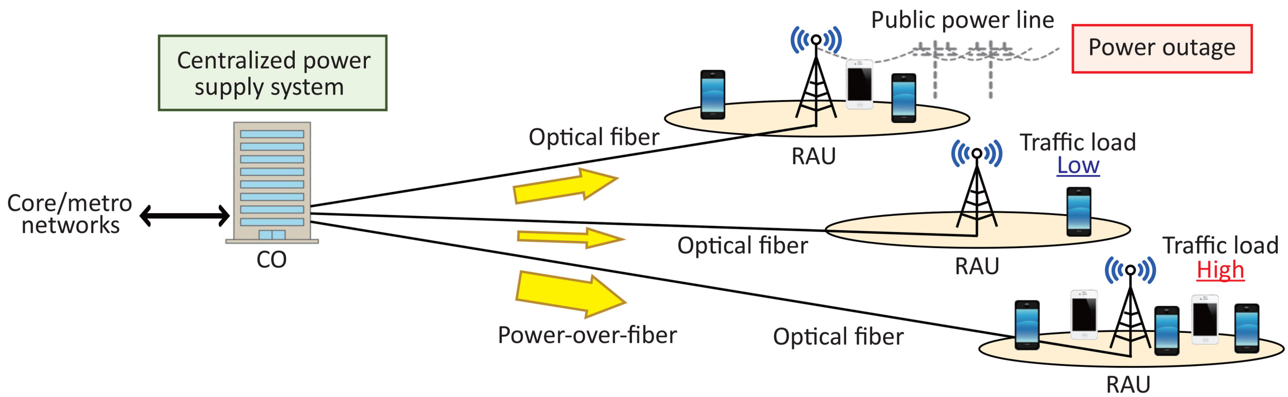


Fig. 2. Example of RoF networks by PWoF for optically powered RAUs. CO: Central office, RAU: Remote antenna unit.

This paper is an extension of an invited talk presented in [14], and presents an overview of PWoF and its applications. Although a review paper summarizing recent results on PWoF, focusing especially on papers presented at the Optical Wireless and Fiber Transmission Conferences (OWPT) [15] from 2019 and 2021, has been published by the same author, separately [16], this paper focuses on the author's work, and its advantages are described in detail. It also introduces key components for PWoF and the experimental demonstrations of PWoF, which enable simultaneous data and electric power transmission utilizing a single optical fiber. In addition, the purpose of this paper is to discuss the practicality and the importance of PWoF and to present the future prospects.

The remainder of this paper is organized as follows. In Section II, the application of PWoF in RoF networks is explained in detail. Section III compares the features of various optical fibers for PWoF, and describes the details of the double-clad fiber (DCF) utilized in this study. Section IV introduces the experimental demonstration of bidirectional data transmission and over 40 W of electric power delivery using a DCF. Section V shows the latest performances of PWoF reported so far, and discusses the feasibility and future perspective of PWoF. Finally, Section VI concludes the paper.

II. PWoF for RoF Networks

Fig. 2 illustrates an example of RoF networks by PWoF for optically powered RAUs. In a simple configuration, the network comprises a CO and several RAUs, and the CO and each RAU are connected by optical fibers. In conventional RoF networks, the power required for RAUs is supplied from the neighboring public power lines, as indicated in the upper RAU; however, when a power failure occurs during natural disasters such as great earthquakes or typhoons, the power supply to the RAU is cut off, and the mobile communication service also stops. In fact, the percentage of RAU outages because of power failure caused by great disasters is very high. For example, in the Great East Japan Earthquake of 2011, approximately 15,000 RAUs were stopped, and it has been reported that 85.3% of the outages were because of power failures [17]. This indicates that communication lines are more robust than public power supply systems in great disasters, and that it is important to maintain the power supply to avoid stopping mobile communication services. In such a situation, if RAUs can be temporarily powered by PWoF using RoF links from the CO, which is equipped with large-scale batteries or private power generators, it will be possible to confirm the safety of family, and obtain disaster information using mobile terminals even in a disaster area with the power outages. Specifically, by installing PWoF in the emergency power supply of RAUs, it is possible to build a mobile communication network that is robust against disasters [6].

PWoF is useful not solely as an emergency, but also as a regular power supply system [10]. If RoF links can always supply power to RAUs, there is no need to install electric power supply facilities and electric power lines. The RAU is connected solely to an optical fiber, which makes the installation work much easier. In addition, RAUs can be easily installed in places where there are no electric power lines nearby. This feature will be useful in future mobile communications that can respond more flexibly to the installation environment of more RAUs.

Another important feature is the remote control of the power supply to RAUs. In general, RAUs are always supplied with a maximum amount of power, regardless of the data traffic. However, in RoF networks, a CO knows the number of mobiles and the amount of data connected to each RAU. Therefore, if the power supplied to each RAU corresponds to the data traffic of the RAU, as illustrated in the middle and lower RAUs in Fig. 1, it is possible to supply the minimum amount of the power required to drive the RAU, and the power consumption of the entire network will be greatly reduced [18], [19]. For example, it has been reported that putting a RAU in "sleep mode" in office areas with few users in the midnight can reduce the power consumption by up to 60% [20]–[22]. The PWoF in RoF networks is expected to further reduce the power consumption because it can control the power more dynamically and efficiently [11].

In such RoF networks, the actual utilization of PWoF requires a power feeding capability of at least several tens of watts that can drive a small and medium-sized RAU without any external power supply systems. As an approach to drive RAUs without achieving sufficient power feeding capability, it has been reported that a battery can be deployed in the RAU in order to use "sleep mode" [23], [24] and to control the electric power supplied to RAUs [25]. However, when these systems are deployed in a larger number of RAUs, maintenance costs

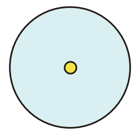
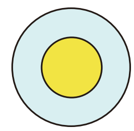
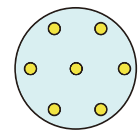
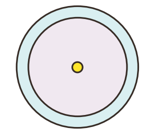
	Single-mode fibers (SMFs)	Multimode fibers (MMFs)	Multi-core fibers (MCFs)	Double-clad fibers (DCFs)
Cross section				
Signal/power transmission	SM core	MM core	Individual core	SM core/ inner cladding
Bandwidth	Broad	Narrow	Broad	Broad (SM core)
Transmission power	Low	Middle	Middle	High (Inner cladding)
Practicability	High	High	Middle	Middle

Fig. 3. Comparison of basic characteristics of optical fibers for PWoF.

due to installment and replacement of batteries will become a significant issue. Therefore, based on the basic configuration illustrated in Fig. 1, it is essential to develop PWoF technologies that greatly exceed the power feeding capability of conventional PWoF technologies. In addition, considering the space saving in optical access cables and its simpler design, the ability to transmit data and power simultaneously over a single optical fiber is also an important issue.

III. Optical Fibers for PWoF

Optical fibers are one of the key components of PWoF, as illustrated in Fig. 1. In particular, these characteristics have a significant impact on the transmission bandwidth and the transmittable optical power. To date, a number of experimental demonstrations of PWoF utilizing various types of optical fibers have been reported so far. The main optical fibers and their basic characteristics are illustrated in Fig. 3.

Single-mode fibers (SMFs) are most commonly utilized in optical fiber communications and are widely used in PWoF [26]−[29]. While the small single-mode (SM) core provides a broadband transmission, the power density can easily increase, which greatly limits the transmittable optical power. Although several PWoF using SMFs have been reported so far, most of them are utilized to drive devices with low power consumption, such as sensors, small cameras, and antenna modules. However, because SMFs have the lowest transmission loss among various optical fibers presently, they are often utilized for long-distance transmission in PWoF.

Multimode fibers (MMFs) have a larger core diameter than SMFs, which are advantageous for optical power transmission [30]−[42]. However, the large multimode (MM) core causes modal dispersion owing to numerous propagation modes, which limit the transmission bandwidth. Although high optical power transmission is possible, the crosstalk between data signals and feed light occurs in the same core when simultaneously transmitting these signals. To avoid the crosstalk, a few approaches have been reported, such as spatially separating data signals and feed light in the MM core [36] and also modulating data signals in the feed light itself [42]; however, if solely the feed light is transmitted over MMFs, the use of MMFs is the most practical method in PWoF [24], [32], [35], [37]−[41].

Multi-core fibers (MCFs) have multiple cores in a single fiber, and are widely utilized for recent high-capacity optical fiber transmissions. In PWoF, simultaneous transmission of data signals and feed light can be easily achieved in a single optical fiber by injecting these signals into individual cores [25], [43]−[45]. It is easy to combine and divide data signals and feed light, and it is possible to increase the transmitted feed light power by utilizing multiple cores; however, it is difficult to transmit a much higher optical power than that of MMFs, owing to the limit of the total core area.

For higher optical power transmission, optical fibers with a larger core are advantageous because they effectively reduce the power density of feed light. However, an SM core is required to provide a broad transmission bandwidth. To meet these requirements, we have proposed and reported PWoF using DCFs [6]−[13], which comprise an SM core and a large inner cladding that surrounds the SM core, as illustrated in Fig. 3. DCFs were originally used as a gain medium for high-power fiber lasers and amplifiers [46]−[49]. In PWoF, ions of rare earth elements are not doped in the SM core. Data signals are transmitted through the undoped SM core, while feed light is transmitted through the inner cladding, which enables simultaneous transmission of high-speed data signals and high-power feed light in a single optical fiber. Owing to the refractive index structure of DCFs, feed light enables us to not solely transmit through the inner cladding, but also through the SM core; however, there is almost no feed light component that can be transmitted through the SM core, satisfying the total internal reflection condition of the SM core. In addition, because the core area of the inner cladding is approximately 240 times larger than that of the SM core, no crosstalk of data signals generated by high-power feed light has been observed in the experimental demonstrations to date [6]−[13].

In silica optical fibers with small cores such as SMFs and MCFs, as the injection power increases, the power density reaches or exceeds the threshold of fiber fuse, which

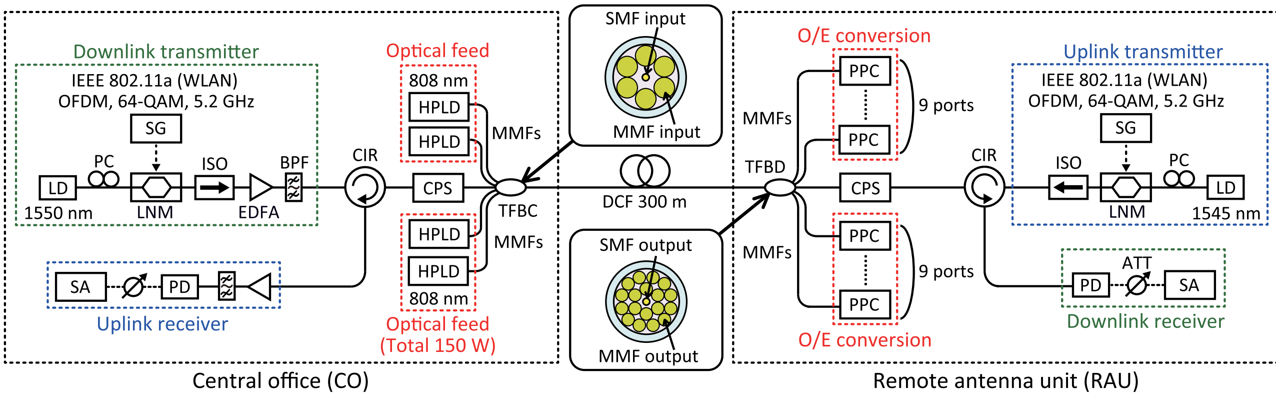


Fig. 4. Experimental setup for PWoF using a 300-m [13]. LD: Laser-diode, PC: Polarization controller, LNM: $LiNbO_3$ modulator, SG: Signal generator, ISO: Isolator, EDFA: Erbium-doped fiber amplifier, BPF: Bandpass filter, CIR: Circulator, CPS: Cladding power stripper, HPLD: High-power laser-diode, MMF: Multimode fiber, TFBC: Tapered fiber bundle combiner, TFBD: Tapered fiber bundle divider, PPC: Photovoltaic power converter, PD: Photodiode, ATT: Variable electrical attenuator, SA: Signal analyzer. Insets show cross sections of (a) TFBC and (b) TFBD.

is a well-known, self-destructive phenomenon that occurs when high-power light is transmitted through an optical fiber [50], [51]. It should be noted that fiber fuse do not always occur when the threshold is exceeded. Indeed, it has been reported that silica optical fibers has resistant to power density in GW/cm^2 class [52]. However, optical power transmission with a high power density dramatically increases the probability of the occurrence of fiber fuse. Therefore, optical power transmission with a higher power density than the threshold is not suitable for deployment in real optical cables, which are easily affected by disturbances such as temperature changes and vibrations.

As optical fibers other than those illustrated in Fig. 3, hollow-core fibers (HCFs) have recently garnered significant attraction in optical fiber communications [53]−[55]. Because HCFs have an air core surrounded by a microstructured cladding, it is possible to achieve various characteristics that are difficult to achieve with glass core fibers, such as ultra-low nonlinearity and ultra-low latency. In PWoF, HCFs are also expected to provide much higher input power tolerance and lower crosstalk between data signals and feed light than glass core fibers; however, when simultaneously transmitting data signals and feed light in the same core, they must be combined and divided using different wavelengths. Therefore, a high power tolerance is required for wavelength selective devices and coupling parts of silica core fibers. Recently, commercialized HCF cables [53] and HCFs with transmission losses lower than those of silica cores [55] have been reported. With further development, HCFs are attractive optical fibers for PWoF. As for other optical fibers, PWoF utilizing plastic optical fibers [56] and large-core microstructure optical fibers [57] have been reported, and the applications that take advantage of the characteristics of each are being studied.

IV. Simultaneous Data and Power Transmission Using a DCF

To demonstrate the feasibility of PWoF using DCFs, our recent results are presented in this Section. Whereas the details are described in Refs. [12] and [13], this paper focuses on the key technologies and representative results that are important for achieving higher performance than those of other studies.

A. Experimental Setup

Fig. 4 illustrates the experimental setup for a PWoF using a 300-m DCF [13]. In this experimental demonstration, the bi-directional (downlink and uplink) data transmission over an RoF link from the CO to a RAU and the electric power delivery to the RAU were performed, based on the RoF network, as illustrated in Fig. 2. For an electrical data signal, which is assumed to be a wireless signal, we utilized one that conforms to the wireless local area network (WLAN) standard with a carrier frequency of 5.2 GHz. Although the signal format is different from the standard used in current mobile communications such as 4th and 5th Generation mobile communication systems (4G/5G), we utilized it in this experiment, because signal formats do not affect the difference in optical data transmission performance with and without feed light if the same fiber with the same length is used. The electrical data signals generated by signal generators (SGs) were converted into analog RoF (A-RoF) data signals by intensity-modulation, with $LiNbO_3$ modulators (LNMs) at the downlink and uplink transmitters. The downlink and uplink A-RoF data signals were simultaneously transmitted into the DCF. The signal wavelengths were 1550 nm and 1545 nm, respectively. As feed light sources, we utilized four commercially available high-power laser-diodes (HPLDs) (K808DA5RN-35.00W-SMA905, BTW Ltd.) with wavelengths of 808 nm. The maximum output power of each HPLD was 35−40 W. The total feed light output power generated by the four HPLDs was 150 W. The four feed lights were injected into to the DCF link. The detailed characteristics of the HPLDs are described in Section IV.B. After the DCF link transmission, the downlink and uplink A-RoF data signals were converted into electrical signals, and the transmission performances were evaluated by error-vector magnitude (EVM) using signal analyzers (SAs) at the downlink and uplink receivers. Here, the downlink A-RoF data signal was amplified by an erbium-doped fiber amplifier (EDFA) before transmission, while the uplink signal was amplified after transmission. This was because the EDFAs were deployed on the CO side to reduce the power consumption of the RAU as much as possible. For the PPC, we utilized a special PPC customized for the PWoF link. The details are described in Section IV.C.

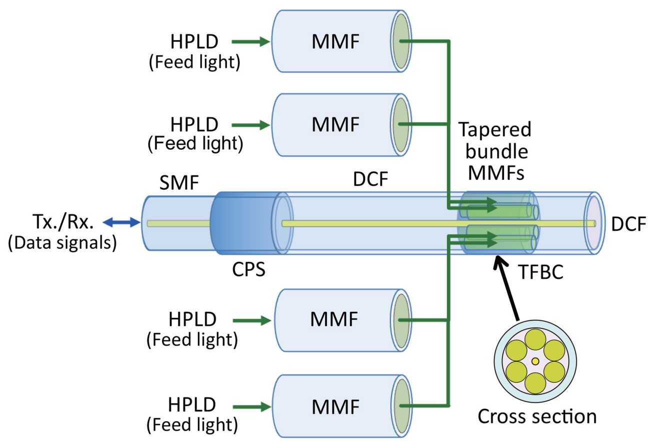


Fig. 5. Configuration of combiner scheme of PWoF.

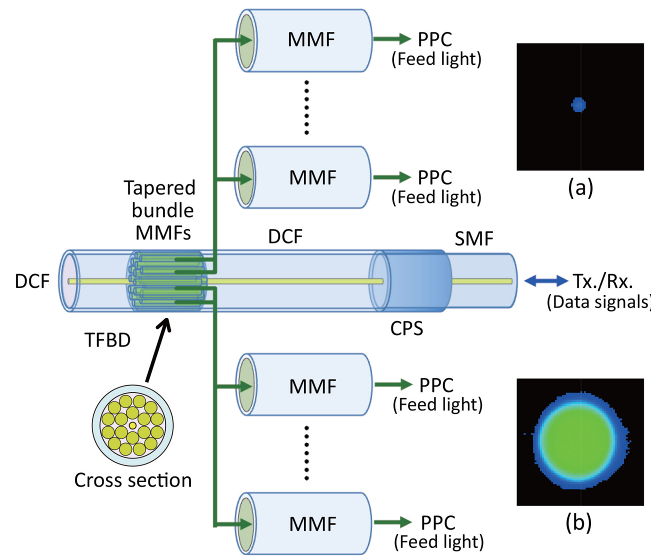


Fig. 6. Configuration of divider scheme of PWoF. Insets show examples of power distribution profiles of (a) SMF and (b) one of MMF outputs.

The key components in the DCF link are cladding power strippers (CPSs), a tapered fiber bundle combiner (TFBC), and a tapered fiber bundle divider (TFBD). In these components, TFBCs are commonly utilized for high-power fiber lasers and amplifiers with DCFs [58], [59]. Fig. 5 illustrates the detailed configurations of the combiner scheme, which comprises a CPS and a TFBC. The CPS had a SMF input and a DCF output ports, and the role of the CPS was to remove the feed light components of the inner cladding of the DCF. Here, the reflected feed light components were removed so that the feed light did not leak to the SMF side. The TFBC was connected to the DCF by fusion splicing. The diameters of the SM core, inner cladding, and outer part of the DCF utilized in this experiment were 8 μm, 125 μm, and 180 μm, respectively. Furthermore, as the DCF had a thin coating, the actual fiber outer diameter was approximately 250 μm, which was the same outer diameter as that of "bare fiber" known as typical coated SMFs. In the middle of the DCF, a TFBC was placed to combine the A-RoF data signals in the SM core and the feed light in the inner cladding. The A-RoF data signals were transmitted directly through the SM core, while the feed light was input to the inner cladding of the DCF using four of the six step-index MMFs (SI-MMFs). The diameters of the MM core and outer layer were 105 μm and 125 μm, respectively. The feed light output from each HPLD was injected into the inner cladding of the DCF through the tapered and bundled MMFs, as illustrated in Fig. 4.

Fig. 6 illustrates the detailed configurations of the original divider scheme, which is basically the reverse configuration of the combiner scheme; however, a large number of MMFs are utilized to extract more of the feed light component from the inner cladding of the DCF. In this experiment, we utilized 18 MMFs. Indeed, by increasing the number of MMFs from 6 to 18, the extraction loss in TFBD was reduced by 0.24 dB. Using this configuration, most of the feed light components were extracted by the 18 MMFs. However, a small amount of the feed light feed leaked out from the TFBDs into the output DCF. The CPS was utilized to remove the feed light component and prevent it from leaking into the cladding of the output SMF. The TFBD was connected to the DCF by fusion splicing. The insets of Fig. 6 illustrate examples of the power profiles of the SMF and one of the six MMF outputs [7]. In the SMF output, solely the profile of the A-RoF data signal component was observed because the feed light component of the inner cladding was well removed by the CPS. In contrast, the MMF output indicated a flat power distribution of the feed light components throughout the MM core. It can be seen that the flat power distribution could be obtained even when the output was from the tapered MMF core in the inner cladding of the DCF, which was much larger than the tapered 18-port MMF core, as shown in Fig. 5.

B. Feed Light Source

In feed light sources, the maximum output power is an important parameter that determines the power feeding capability of PWoF. Regarding HPLDs, because it is necessary to inject feed light generated by an HPLD into an optical fiber, the optical power that can be injected into the optical fiber depends not solely on the power density, but also on the core diameter of the optical fiber.

The four HPLDs utilized in this experiment were fiber-pigtailed HPLDs, which were connected to SI-MMFs with a core diameter of 105 μm. The fiber outputs were directly fused to the TFBC. Fig. 7 illustrates the output power and electrical-to-optical (E/O) conversion efficiency of one of the HPLDs while altering the current. The conversion efficiency was calculated as the ratio of the power required to drive the HPLD to the optical power at the fiber output. The electric power was calculated from the product of the current and voltage applied to the HPLD. The power required to control the temperature of the HPLD was not included. As the current increased, the output power linearly increased, and the maximum output power was reached 40 W. In contrast, the E/O conversion efficiency was not constant. As the current increased, the E/O conversion efficiency increased. At an output power of 40 W, the efficiency was approximately 45%. Because the HPLDs were commercial

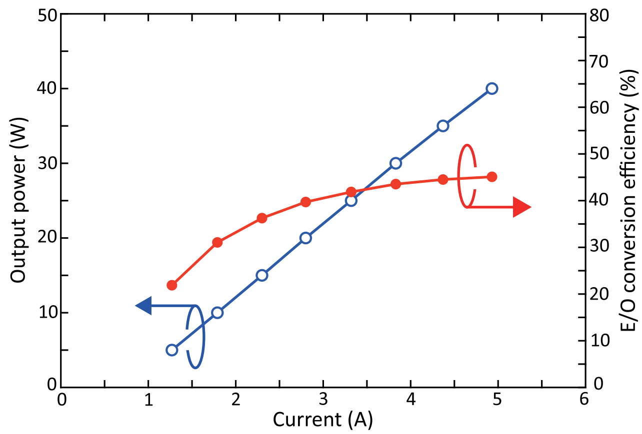


Fig. 7. Output power and E/O conversion efficiency of one of HPLDs while altering current.

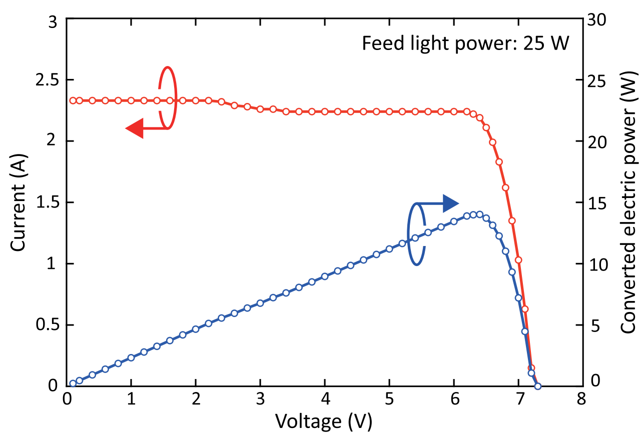


Fig. 8. IV and PV curves of PPC at optical input power of 25 W.

products for experimental use, the E/O conversion efficiencies were not very high. Recently, a few HPLDs with E/O conversion efficiencies exceeding 65% have been reported [60], and the efficiencies of future HPLDs are expected to be improved.

C. *Photovoltaic Power Converter (PPC)*

As illustrated in Fig. 1, PPCs are one of the key components for PWoF to convert transmitted optical power into electric power to drive any electric equipment [61]–[63]. In PPCs, the maximum optical power that can be input to the PPC and optical-to-electrical (O/E) conversion efficiency are important parameters for obtaining higher electric power. In our experiments, we implemented a customized PPC with a vertical epitaxial monolithic heterostructure architecture (VERSA) design that exhibits high performance in both the parameters [64], [65]. The PPC comprised gallium arsenide (GaAs), and had the highest O/E conversion efficiency in the wavelength range of 800 nm to 850 nm, which included the output wavelength of the HPLDs. The PPC had a common fiber connector input (FC/PC connector), and the size of the PPC was approximately $9 \times 3 \times 3$ cm. Fig. 8 illustrates the current voltage (IV) and power voltage (PV) curves of the PPC when the optical input power was set to 25 W. In this experimental demonstration,

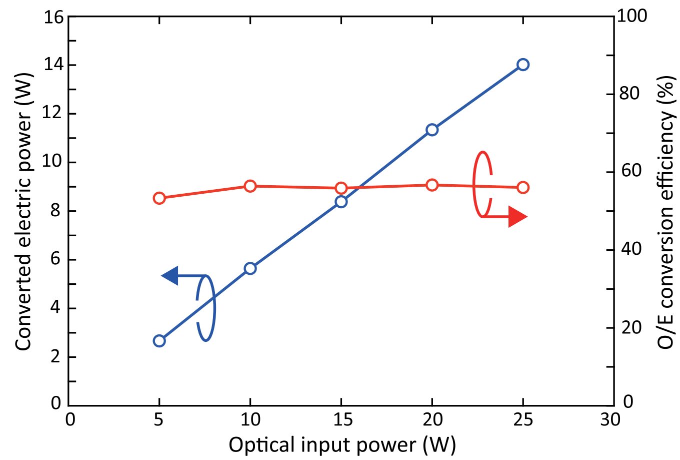


Fig. 9. Converted electric power and O/E conversion efficiency of PPC.

solely a maximum optical power of approximately 4.5 W was input to the PPC; however, to present the detailed performance evaluation, a maximum optical power of 25 W was utilized in this measurement. The current maintained a constant value to some extent as the voltage increased; however, the current decreased rapidly when the voltage exceeded a certain level. In contrast, the converted electric power increased linearly and decreased rapidly when the voltage exceeded a certain level. The voltage at which this electric power is at its maximum is called the maximum power point (MPP). The MPP of the PPC was approximately 6.4 V.

Fig. 9 illustrates the converted electric power and O/E conversion efficiency of the PPC while altering the optical input power. As the optical input power increased, the converted electric power also increased almost linearly without saturation. It was determined that the optical power input of 25 W provided the electric power of over 14 W. The conversion efficiency was approximately 56%. Because the losses in the PPC were mainly dissipated as heat energy, the PPC was equipped with a fan-less heat sink. The size of the heat sink was approximately $14 \times 10 \times 6.5$ cm. The weight of the PPC, including the heat sink was approximately 650 g. Because of the high conversion efficiency of the PPC, there was no significant heat increase of the PPC itself, and no active cooling system with the required electric power was used.

D. *Data and Power Transmission Performances*

Fig. 10 illustrates the EVM penalties to the back-to-back signal of the downlink- and uplink-transmitted A-RoF data signals and the delivered electric power as a function of the total feed light power injected into the PWoF link. To evaluate the effect of simultaneous feed light transmission of up to 150 W on the transmission performance of the A-RoF data signals, the EVM penalties were measured. To generate the A-RoF data signal, the modulation signal format used in this experiment was 64-quadrature amplitude modulation (64-QAM), orthogonal frequency division multiplexing (OFDM) signal in accordance with IEEE 802.11a WLAN standard. The carrier frequency and the transmission speed of the packet were 5.2 GHz

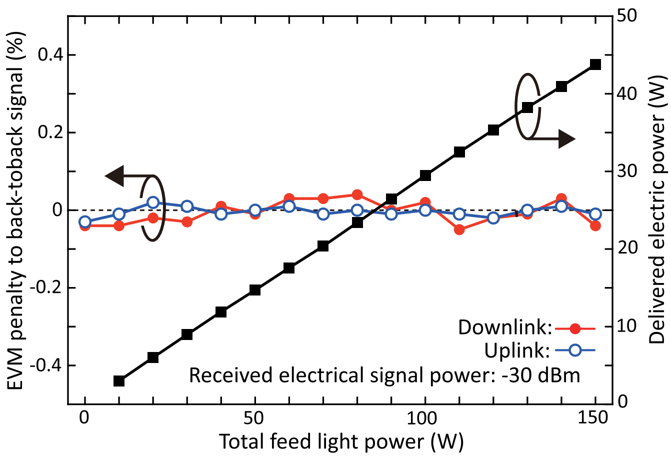


Fig. 10. EVM penalties to back-to-back signal of transmitted A-RoF data signals and delivered electric power as a function of total feed light power injected into PWoF link.

TABLE I
POWER BUDGET OF PWOF LINK

Component	Loss (dB)
Tapered fiber bundle combiner (TFBC) (6 MMF input ports)	0.45
300-m DCF (3.3 dB/km@808 nm)	1.45
Tapered fiber bundle divider (TFBD) (18 MMF output ports)	0.76
Photovoltaic power converter (PPC) (O/E conversion efficiency of 54%)	2.57

and 54 Mbit/s, respectively. In this experiment, the EVM value of the back-to-back signal, which means that the signal transmitted directly between CO and RAU without the PWoF link, was 0.84% when the received electrical signal power was set to −30 dBm. Although the EVM value needs to be less than 5.6% for the wireless signal format used in this experiment for real deployment, the obtained EVM penalties were less than 0.05%, even if the feed light power was increased up to 150 W. This result indicates that the simultaneous transmission of the high feed light power does not affect the transmission performance of the A-RoF data signals. As for the power transmission capability of the PWoF, as the feed light power injected into the PWoF link increased up to 150 W, the delivered electric power was increased up to 43.7 W. Then, the power transmission efficiency defined as the power ratio between the total feed light power and the delivered electric power was approximately 30%.

The power budget of the PWoF link is presented in Table I. The largest loss was observed in the O/E conversion in the PPC. Because the loss in the DCF was also highly dependent on the wavelength of the feed light utilized, the selection of the feed light wavelength will be important for PWoF with longer DCFs in the future. Here, considering the electric power transmission efficiency as well as conventional electric power supply systems,

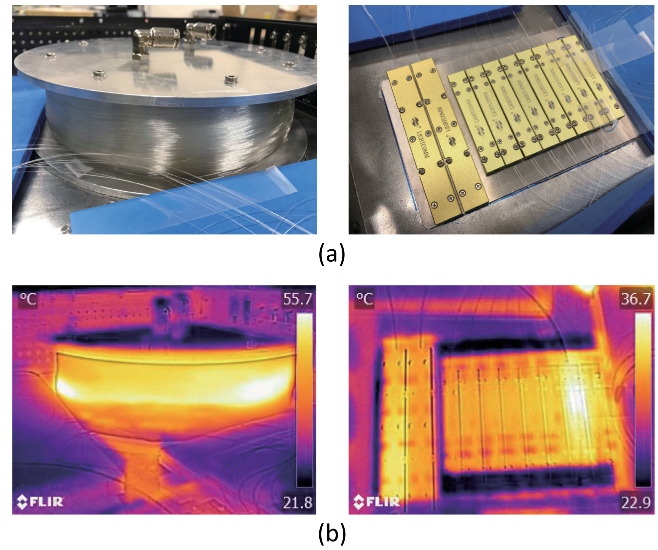


Fig. 11. Examples of (a) photos and (b) images taken with a thermography camera of PWoF link.

the E/O conversion efficiency in HPLD also needs to be considered. As described in Section IV.B, because the conversion efficiency of the HPLD is 45%, the electric power transmission efficiency of the PWoF link is approximately 13.5%. This value is extremely low compared to the efficiency of high-voltage lines of common electric power supply systems installed underground or on poles, but not as low as that of low-voltage lines for indoor use. If the conversion efficiency of HPLDs and PPCs will be improved, the power transmission efficiency is expected to be comparable to that of low-voltage lines, especially longer power lines. For example, Power-over-Ethernet (PoE), which will be discussed in the next Section, has been standardized for use within 100 m because it has a transmission loss of approximately 30% at 100 m if there is no extended power function. In addition, it is also important to use feed light wavelength with lower loss in optical fibers, since the loss becomes dominant when transmitting over longer distances. However, since the conversion efficiencies of HPLDs and PPCs change with the change of the feed light wavelength, it is important to use the optimal feed light wavelength according to the transmission distance.

An important feature of the PWoF is the high linearity of the feed power control, as illustrated in Fig. 10. This is also related to the linearity indicated for the characteristics of the HPLD and the PPC, as illustrated in Figs. 7 and 9, respectively. Because PWoF does not require AC/DC and DC/AC converters, the high linearity can facilitate remote control when adjusting the appropriate power supply depending on the mobile data traffic of RAUs, as described in Section II.

E. Stability and Reliability

As aforementioned, the PWoF link has insertion losses, and most of these losses are dissipated as heat; therefore, it is important to evaluate the time variation of the temperature to assess the stability and reliability of the PWoF link. Fig. 11 illustrated photographs of the main components of the PWoF

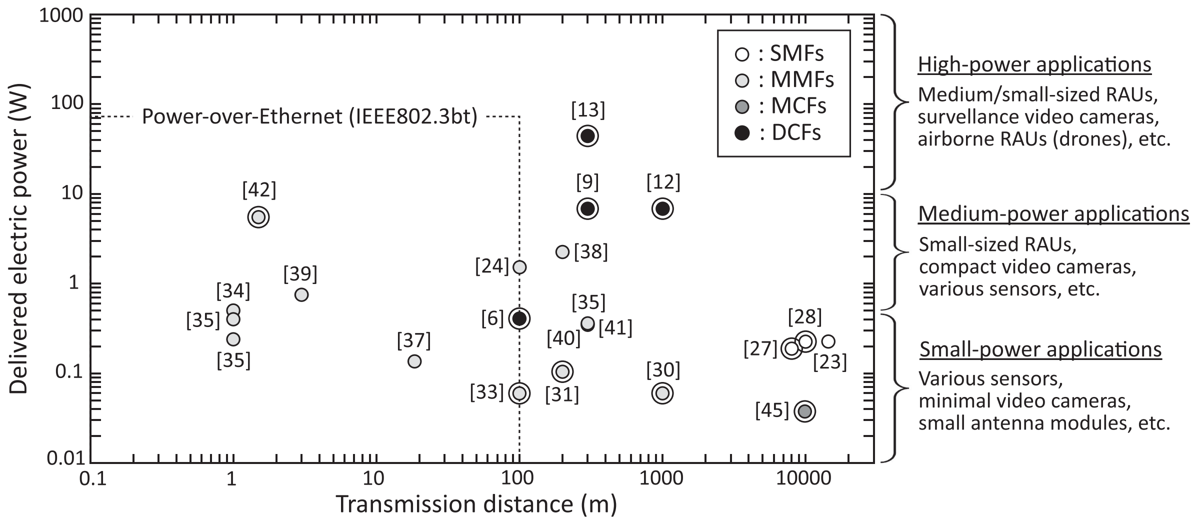


Fig. 12. Delivered electric power versus transmission distance in reported experimental demonstrations of PWoF using various types of optical fibers. Double circles show simultaneous data and power transmissions using a single optical fiber.

link and its thermographic images. For these measurements, to evaluate the thermal effects at longer transmission distances, the 1 km DCF link was utilized [12], instead of the 300 m DCF link, as illustrated in Fig. 4. Accordingly, it was confirmed that the temperature of each element except for the DCF, as shown in the center part of the left picture of Fig. 11(b), did not exhibit a critical increase after 10 min. In this setup, the DCF was bent around a drum, and the heat induced by the transmission loss accumulated in the drum. However, in real deployment, it will be easy to diffuse the heat, because DCFs are installed in a straight line without bending around drums. It was also confirmed that the power transmission efficiency was almost unchanged during the 10 min measurement period. In addition, the PPCs utilized indicated almost no temperature increase in response to optical input, confirming that stable electric output and conversion efficiency can be maintained, as indicated in Ref. [61]. These results indicate that the PWoF link has high stability and reliability as a power supply system.

V. Discussion

The most important performance factors in PWoF are the power feeding capability and its transmission distance. Fig. 12 illustrates the delivered electric power versus the optical power transmission distance in the remarkable demonstrations of PWoF using SMFs [23], [27], [28], MMFs [24], [30], [31], [33]–[35], [37]–[42], MCFs [45], and DCFs [6], [9], [12], [13]. The single circles indicate that data signals and feed light are transmitted over each different optical fiber, while the double circles indicate that they are simultaneously transmitted over a same optical fiber. These demonstrations are for the purpose of data and power transmissions, and clearly describe the experimental data of the delivered electric power and optical power transmission distance. To the best of the author's knowledge, no other demonstrations have been reported to exceed these performances, as illustrated in Fig. 12. SMFs have the lowest loss in all the optical fibers, and by using a longer feed light wavelength such as 1480 nm, longer transmission distances are achieved. However, the delivered electric power is generally lower than those of the MMFs and DCFs, because the optical transmittable power is strictly limited, owing to the small core area, as mentioned in Section III. MMFs are widely utilized in PWoF, and there have been several demonstrations in PWoF. Indeed, some of these demonstrations of the electric power delivery exceeding 1 W, and simultaneous transmissions with data signals have been reported. However, as the transmission distance increases, the data rate decreases significantly. While MCFs have a transmission bandwidth comparable to SMFs, the transmission loss is larger than that of SMFs. Increasing the number of cores used can improve the delivered electric power. However, the power transmission efficiency is not as high as that of SMFs. DCFs have a larger inner cladding than the cores of SMFs and MMFs, and achieve higher electric power delivery in simultaneous transmission with high-speed data signals. Hence, it can be observed that the use of DCFs has a higher performance compared to other optical fibers. In particular, the delivered electric power of the PWoF presented in Session VI [13], is the top record for simultaneous transmission with data signals, to the best of the author's knowledge.

In PWoF, the delivered electric power determines the electrical equipment that can be driven, thus, the applications also vary depending on the electric power. The right side of Fig. 12 illustrates three future applications roughly classified by the three electric power levels. In small-power applications, a typical application is a sensor device. Because most of the sensors can be driven with a low power, PWoF is widely utilized to drive various types of sensors. PWoF can also be utilized to drive small video cameras and antenna modules. In medium-power applications, it is possible to drive small RAUs, compact cameras and sensors with higher performance. Indeed, a few antenna modules for small RAUs have been reported at the power level [38], [43]. In high-power applications, where the delivered electric power is over 10 W, it will be possible to drive medium-sized RAUs and surveillance cameras, which are widely utilized in actual applications. Airborne RAUs using drones will be included in applications related to RAUs. The main challenge in using drones as RAUs is the limitation of flight time due to the battery capacity. One way to address this challenge is to utilize optically powered drones by PWoF, which makes it possible for drones to fly for unlimited flight time by always being powered using optical fibers [66]. If more power can be transmitted by an optical fiber, this type of usage can be considered.

PoE, which enables data and power transmission using a single Ethernet cable, is a competing technology for PWoF. The latest standard is IEEE 802.3bt, and the specifications are indicated in the area surrounded by the dotted line in Fig. 12. In PWoF, it can be observed that the performance of the delivered electric power has reached a comparable specification of PoE, and the transmission distance has a much longer performance than that of PoE. Furthermore, PWoF provides a much higher data transmission capacity, which is extremely advantageous for future mobile communication applications. In the future, it is expected that various applications will be developed by taking advantage of the unique characteristics of optical fibers as a power line.

VI. Conclusion

This study reviewed PWoF technologies for future mobile communications. After introducing PWoF using various kinds of optical fibers and their features, our experimental demonstrations were described in detail. While power supply systems are essential for communications, optical fibers are the most suitable communication lines for high-speed data transmission. This means that PWoF is a more effective means of integrating communication and power in the future. In particular, the utilization of DCFs in PWoF, which provides high-speed data communication and power transmission capable of driving a practical RAU with a single optical fiber, has high potential as a future infrastructure technology.

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