Power-over-Fiber for Radio-over-Fiber Links

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Abstract *This paper introduces simultaneous data and power transmission by power-over-fiber using a single optical fiber for driving a remote antenna unit in radio-over-fiber-based mobile communication networks. This paper also discusses the future prospects of power-over-fiber.*

Introduction

Radio-over-fiber (RoF) is an essential technology for future mobile communication networks[1]. In particular, smaller cell networks will require more remote antenna units (RAUs) and RoF links to connect them to a central office (CO). Thus, it will be very important to simplify the installation and management of the RAUs.

Power-over-fiber (PWoF) is a practical way to transmit power using optical fibers. In this regard, it is desirable to be able to simultaneously transmit data and power using a single optical fiber from the perspective of fiber installation space. In RoF networks, if RoF links can be used to supply the power to drive RAUs, the installation of the RAUs become much easier without electric wiring works, and it is possible to simultaneously manage the communication and power supply of the RAUs using the RoF links.

In this paper, an overview of PWoF and their key components are presented. It also introduces our experimental demonstration of PWoF, which enables simultaneous 43.7-W electric power and RoF data transmission using a single optical fiber. The practicability and future prospect of PWoF is also discussed.

Power-over-Fiber (PWoF)

PWoF comprises light sources, optical fibers, and photovoltaic power converters (PPCs). Figure 1 shows the basic scheme of PWoF. A feed light generated by a light source is transmitted into an optical fiber, and the transmitted feed light power is converted into electric power by a PPC to drive any electrical equipment. As light sources, high-power laser-diodes (HPLDs) and fiber lasers are commonly used.

Optical fibers are key components for PWoF. When transmitting data and power over a single optical fiber, the structure has a significant impact on its data and power transmission performance. Table 1 shows the cross sections and features of various types of optical fibers. Single-mode fibers (SMFs) are the most common fibers. Although the small core provides broad signal transmission bandwidth, it severely limits transmittable power due to the high-power density of the core. Multi-mode fibers (MMFs) can increase transmittable power, but the signal transmission bandwidth is limited due to modal dispersion[2],[3]. Multi-core fibers (MCFs) simultaneously transmit data and power using multiple cores into a single optical fiber[4]. The transmittable power depends on the number of cores of the MCF. Double-clad fibers (DCFs) comprise a single-mode (SM) core and an inner-cladding that surrounds the SM core. By transmitting data into the core and feed light into the inner cladding, broad transmission bandwidth and higher transmittable power can be provided simultaneously. As representative achievements, we have reported several PWoF demonstrations using DCFs so far[5]–[9].

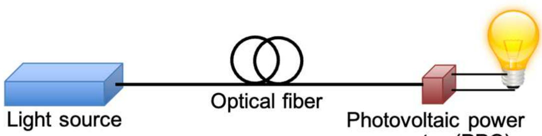
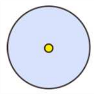
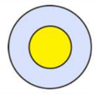
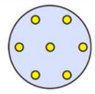
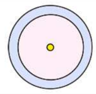


Fig. 1: Basic scheme of PWoF

Tab. 1: Cross sections of various types of optical fibers

	SMF	MMF	MCF	DCF
Cross section				
Transmission bandwidth	Broad	Narrow (Modal disp.)	Broad	Broad
Transmittable power	Low	Middle	Middle	High

PPCs are also key components for PWoF, and significantly affect the power transmission performance. Since lights injected into PPCs assume laser sources with a much narrower optical spectrum than sunlight, PPCs generally have higher conversion efficiency than those of solar cells. The operating wavelength of PPCs is determined by the composition material. By selecting an appropriate composition material, a feed light power with a desired wavelength can be converted to electric power with a higher efficiency.

The advantage of entire PWoF system is robust against electromagnetic interference (EMI), since optical fibers are non-conductive power lin-

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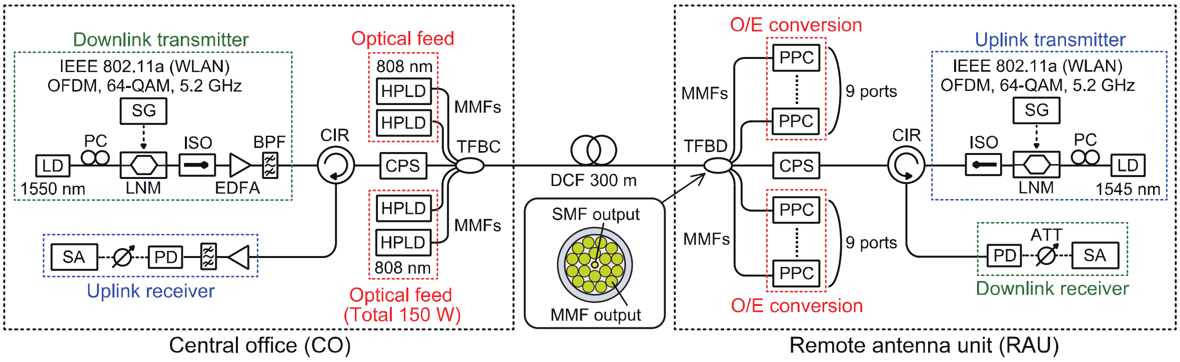

Fig. 2: Simultaneous 43.7-W electric power and A-RoF data transmission by PWoF using a 300-m DCF[9]. LD: Laser-diode, PC: Polarization controller, SG: Signal generator, LNM: $LiNbO_3$ modulator, ISO: Isolator, EDFA: Erbium doped fiber amplifier, BPF: Bandpass filter, CIR: Circulator, SA: Signal analyzer, PD: Photodiode, HPLD: High-power laser-diode, CPS: Cladding power stripper, MMF: Multimode fiber, TFBC: Tapered-fiber-bundle combiner, TFBD: Tapered-fiber-bundle divider, PPC: Photovoltaic power converter. Inset shows cross section of TFBD.

es. It is effective for supplying the power to RAUs that radiate radio-frequency (RF) signals from the antennas. In addition, since RAUs are generally placed at high altitudes, RAUs are often damaged by lightning strikes. However, by using non-inductive power lines, it is possible to block the reverse current to the electric power equipment and minimize the damage.

Over 40-W PWoF using a DCF

Since the electric power to drive a small cell RAU exceeds 10 W, a PWoF scheme capable of transmitting higher power is required. In this regard, we have reported several PWoF demonstrations using DCFs. Figure 2 shows the experimental setup for the PWoF using a 300-m DCF[9]. In the downlink and uplink transmitters, optical analog RoF (A-RoF) data signals were generated by signal generators (SGs), laser-diodes (LDs), and $LiNbO_3$ modulators (LNMs). The modulated data was based on orthogonal frequency division multiplexing (OFDM), 64-quadrature amplitude modulation (64-QAM) signal with a carrier frequency of 5.2 GHz. The A-RoF data signals were simultaneously transmitted into the 300-m DCF. The diameters of the SM core and the inner cladding were 8 μm and 125 μm, respectively. After bidirectional transmission, the A-RoF signals were converted to electrical signals by photodiodes (PDs), and the signal qualities were measured by signal analysers (SAs) in terms of error-vector magnitude (EVM).

Feed lights for optical power feeding were generated by four high-power laser-diodes (HPLDs) with wavelengths of 808 nm. The maximum output power of each HPLD was 35 W to 40 W. The maximum total output power of the HPLDs was 150 W. The downlink A-RoF data signal and the feed light were combined by a tapered-fiber-bundle combiner (TFBC), and injected into the SM core and the inner cladding of the DCF, respectively. After transmission, they were divided by a tapered-fiber-bundle divider (TFBD). Cladding power strippers (CPSs) located at the input of the TFBC and the output of the TFBD were used to remove the reflected and transmitted feed light components in the inner cladding. In the TFBD, the feed light was divided into 16 MMF output, and injected to each PPC, and converted into electric power.

In this study, two approaches were executed to increase the delivered electric power. One is the improvement of insertion loss of TFBD. While the transmission loss of DCFs is determined by the wavelength of feed light, the insertion loss of TFBD can be reduced by increasing the number of MMF output port. The inset of Fig. 2 shows the cross section of the TFBD. In this scheme, the feed light component is extracted from the MMF output core area; therefore, to efficiently extract the feed light component from the inner cladding, it is better to use a larger number of MMF outputs. In this work, the insertion loss of the TFBD was

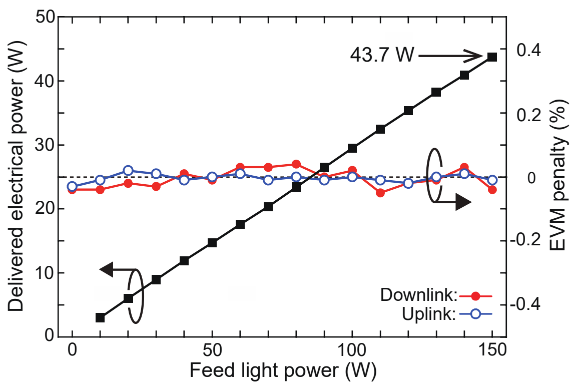

Fig. 3: Delivered electric power and EVM characteristics of downlink- and uplink-transmitted A-RoF data signals

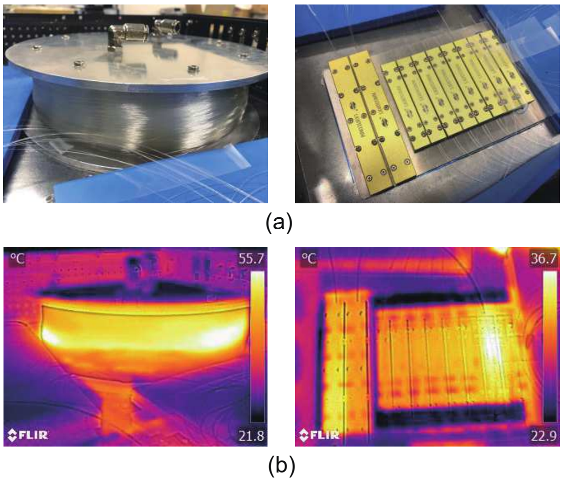

Fig. 4: Photographs of (a) main components of PWoF and (b) its thermographic images

reduced by increasing the MMF output from 6-port to 18-port.

The other is to improve the conversion performance of PPCs. In this work, a specially customized PPC with vertical epitaxial heterostructure architecture was used[10]. The PPC provided over 20 W input power and high conversion efficiency of over 50% at 808 nm, which were available to 150 W feed PWoF scheme we constructed.

Figure 3 shows the delivered electric power and EVM characteristics of the bidirectional transmitted A-RoF data signals as a function of the feed light power injected into the PWoF. As the feed light power increased, the delivered electric power was linearly increased up to 43.7 W. The linear response is very useful for controlling the supplied power as a power supply system. In addition, to evaluate the signal transmission performance under the high-power feeding of up to 150 W, the EVM penalties to back-to-back signal of the downlink- and uplink-transmitted signals were measured. Although the EVM value needs to be less than 5.6% for 64-QAM signals, the EVM penalties were less than 0.05% even if the feed light power was increase up to 150 W. This result shows that the transmission performance is almost equivalent to those of conventional A-RoF data transmission even when electric power greater than 40 W is simultaneously delivered into the same optical fiber.

Safety and stability of high-power PWoF

In the presented PWoF, the feed light power of up to 150 W was injected into the DCF. However, since the core area of the inner cladding of the DCF is more than 240 times larger than that of SM core, the power density is not as high as common power at output of high-power optical amplifiers in optical fiber communications using SMFs. However, since the actual power transmitted into the fiber is so high, it will be necessary to install automatic laser shutdown function in feed light sources, assuming strong bending and disconnection.

To evaluate the stability of the PWoF, we also measured the temporal variation of the temperature of the main components and the optical transmission power of the entire system. Figure 4 shows the photographs of main components of the PWoF and its thermographic images. In these measurements, we confirmed that high stability could be maintained even though a 1-km DCF was used[8].

Future perspective

In order to be able to drive more various types of RAUs, it is desirable to realize a PWoF that can supply over 100 W electric power. Therefore, it is very important to increase feed light power and improve power transmission efficiency. For the power transmission efficiency, the fiber transmitssion loss becomes dominant as the transmitssion distance becomes longer. Therefore, it is effective to use lower-loss feed light wavelengths. In addition, it will be very important to develop and improve the performance of PPCs in those wavelength bands.

In the near future, the demand for RAUs, which are capable of broadband communications and easy to install and manage, is expected to acelerate rapidly not only in mobile communications but also in the field of Internet of Things (IoT). The presented PWoF is expected to play an important role in meeting these demands.

Conclusions

This paper introduced PWoF for driving a RAU in mobile communication networks. As an our demonstration, simultaneous 43.7-W electric power and A-RoF transmission was also presented. To the best of our knowledge, this is the highest electric power transmission with data signals using an optical fiber, Further development of PWoF and expansion of its application technologies to various fields are expected in the future.

Acknowledgements

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