Power-Over-Fiber Using a Pure-Silica Inner-Cladding Double-Clad Fiber and 976 nm Photovoltaic Power Converter for Improving Power Transmission Efficiency

Yuya Yaguchi(1), Yu Miyakawa(1), Souya Sugiura(1), Shih-Chun Lin(2), Suresh Subramaniam(3), Hiroshi Hasegawa(4), Denis Masson(5), Simon Fafard(5), Motoharu Matsuura(1)

(1) The University of Electro-Communications, y.yaguchi@uec.ac.jp
(2) North Carolina State University
(3) George Washington University
(4) Nagoya University
(5) Broadcom, Inc.

Abstract *We present power-over-fiber transmission using a pure-silica inner-cladding double-clad fiber. We successfully achieved good bidirectional transmission characteristics of analog radio-over-fiber signals at 1550 nm band and improved power transmission efficiency of laser input light at 976 nm with a simple configuration using a single fiber. ©2024 The Author(s)*

Introduction

Radio-over-fiber (RoF) is an essential technology for future mobile networks [1],[2]. As the carrier frequency of wireless signals becomes higher and higher, the cell area of remote antenna units (RAUs) will become smaller and smaller, requiring more RAUs to be deployed. In addition, it will become increasingly important to install RAUs in areas without power facilities and to enable them to operate even in the event of power failures such as power outages.

In RoF-based mobile networks, power-over-fiber (PWoF) is a means of supplying power to RAUs using optical fibers [3]. PWoF is effective as an emergency power supply in the event of a power outage of RAUs and as a simple technology to install for RAUs that does not require electrical facilities and wiring.

Our group has previously proposed PWoF using double-clad fibers (DCFs) [4]-[8], and demonstrated RoF signal transmission with over 40 W electric power [7]. Recently, research on fronthaul network architecture using DCFs has also been reported [9]. However, the available feed light wavelengths for power transmission were strictly limited, resulting in a large increase in loss as the transmission distance was extended [6]. In addition, complicated components were required for combining/demultiplexing RoF signals and feed light for the DCF.

This study presents a PWoF transmission using a pure-silica inner-cladding DCF (PSIC-DCF) and a high-power photovoltaic power converter (PPC) with a high optical-to-electrical (O/E) conversion efficiency at a wavelength of 976 nm. The inner-cladding of the PSIC-DCF for power transmission is composed of pure silica, resulting in much lower loss than that of conventional DCFs over a wide wavelength range. As a result, we demonstrate much improved high bi-directional transmission characteristics of RoF signals and simultaneous power transmission of a 20 W feed light in a simple and low-loss configuration using a single 300 m PSIC-DCF.

Pure-Silica Inner-Cladding Double-Clad Fiber (PSIC-DCF)

The DCFs used in our previous studies had additional doped materials in the inner-cladding to form the core duplex structure, resulting in higher transmission losses with increasing wavelength loss dependence as shown in Table 1. Therefore, we had to use a feed light in the 808 nm band, which has the lowest loss of the DCF.

To overcome this problem, we introduced a PSIC-DCF with an inner-cladding composed of pure-silica core. Table 1 shows that PSIC-DCF have significantly lower losses and a wavelength loss dependence more akin to that of conventional silica fibers. The numerical aperture (NA) of the inner-cladding is also reduced by using a PSIC-DCF and provides a better match for using a conventional WDM coupler (WDMC) with a low insertion loss. Therefore, this study introduces a

Tab. 1: Transmission loss and numerical aperture (NA) of previous DCF and PSIC-DCF.

	Transmission loss of inner-cladding (dB/km)				NA	
	808 nm	976 nm	1315 nm	1550 nm	SM core	Inner-cladding
Previous DCF	3.3	11.3	26.3	67.8	0.14	0.45
PSIC-DCF	3.15	1.46	1.29	1.24	0.19	0.22

ISBN: 978-3-8007-6426-6

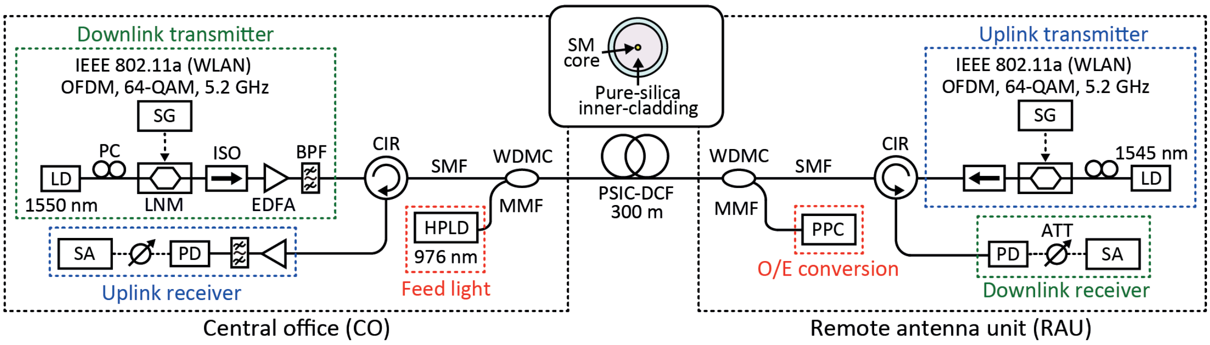


Fig.1: Experimental setup for PWoF using a 300m PSIC-DCF. LD: Laser-diode, PC: Polarization controller, LNM: $LiNbO_3$ modulator, SG: Signal generator, ISO: Isolator, EDFA: Erbium-doped fiber amplifier, BPF: Bandpass filter, CIR: Circulator, SMF: Single-mode fiber, HPLD: High-power laser-diode, MMF: Multimode fiber, WDMC: Wavelength-division-multiplexing coupler, PPC: Photovoltaic power converter, PD: Photodiode, ATT: Variable electrical attenuator, SA: Signal analyzer.

PSIC-DCF with a feed light wavelength at 976 nm, which is in a low-loss wavelength (1.46 dB/km), and where commercially high-power light sources for PWoF are abundant.

Experimental Setup

The experimental setup for PWoF using a PSIC-DCF is shown in Fig. 1. The setup consists of a central office (CO) and RAU sides. For downlink- and uplink transmitters, we used an analog-RoF (A-RoF) signals modulated using an electrical data signal based on IEEE802.11a with a carrier frequency of 5.2 GHz. A seed light generated from a laser-diode (LD) was injected into a $LiNbO_3$ modulator (LNM) for external modulation. A polarization controller (PC) was used to adjust the state of polarization of the seed light input to the LNM. The electrical data signal was generated from a signal generator (SG). The wavelengths of the downlink and uplink A-RoF signals were 1550 nm and 1545 nm, respectively. After amplification using an erbium-doped fiber amplifier (EDFA), the downlink A-RoF signal was passed through a circulator (CIR), and combined with a feed light generated from a 976 nm high-power laser-diode (HPLD) using a wavelength-division-multiplexing coupler (WDMC). After 300 m PSIC-DCF transmission, the A-RoF signal and the feed light were divided using a WDMC. The diameters of the single mode (SM) core, inner-cladding, and outer cladding were 5 μm, 105 μm, and 125 μm, respectively. The signal was converted into electrical signal using a photodiode (PD), and the signal quality was measured using a signal analyzer (SA). The feed light power was converted into electric power using a specially customized photovoltaic power converter (PPC). The details are described in the next section. The uplink A-RoF signal is simultaneously transmitted over the same path in the opposite direction, and the signal quality is evaluated at the CO. The difference is that an EDFA is placed at the CO to reduce the power consumption of the RAU in the uplink transmission.

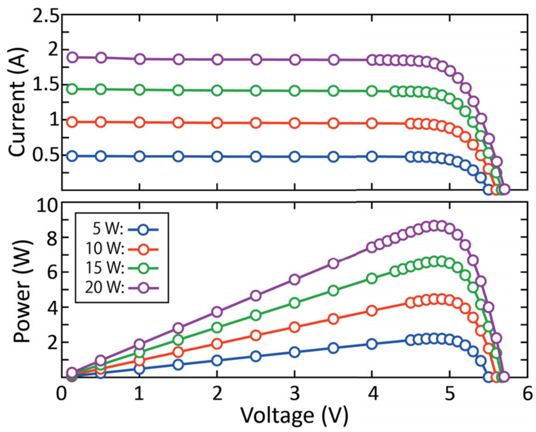


Fig.2: T(a) I-V and (b) P-V characteristics of PPC while changing feed light power input to PPC.

978 nm Photovoltaic Power Converter

PPCs play an important role in PWoF in driving remote equipment. In such PPC, higher available input power and higher O/E conversion efficiency are desirable. In this study, a specially customized PPC with a vertical epitaxial heterostructure architectures (VEHSA) design [10],[11] was used. Figure 2 shows the current-voltage (I-V) and power-voltage (P-V) characteristics of the PPC for various feed light powers input to the PPC. The ideal I-V and P-V curves were observed for all the feed light powers, and the voltage at the maximum power point (V_{mp}) was approximately 4.8 V. The average O/E conversion efficiency was approximately 43.7%. This result greatly exceeds the performance of commercial products at 976 nm, making this PPC another effective component in reducing losses in the proposed PWoF system with PSIC-DCF.

Experimental Results

To evaluate the power transmission efficiency defined as the power ratio between the feed light power input to the PSIC-DCF and input to the PPC, we measured the transmitted optical power. The result is shown in Fig. 3. As the feed light

ISBN: 978-3-8007-6426-6

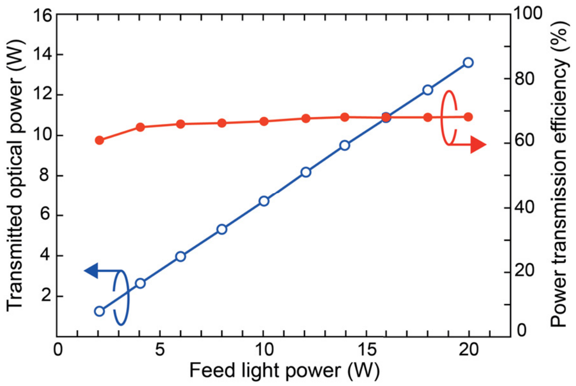
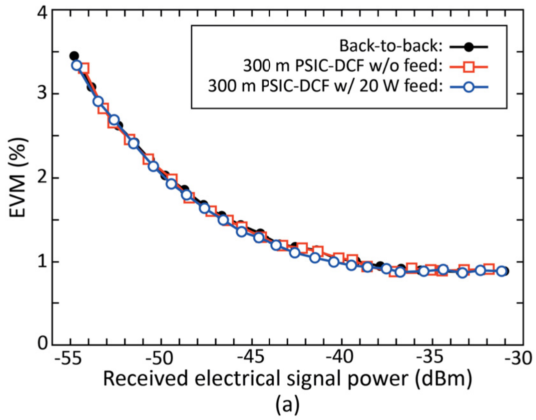


Fig.3: Transmitted optical power and power transmission efficiency while changing feed light power.



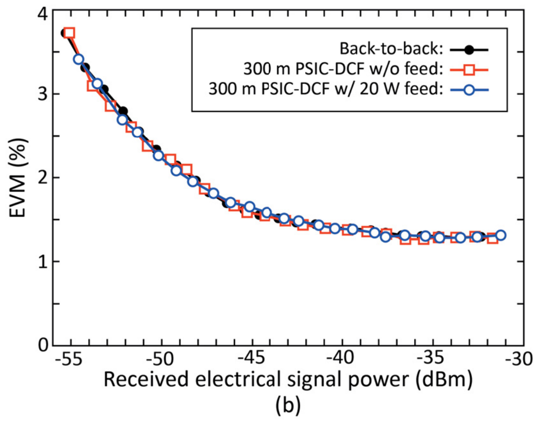


Fig.4: EVM characteristics of (a) downlink-transmitted and (b) uplink-transmitted A-RoF signals.

power increased, the transmitted optical power was linearly increased. In the 20 W feed light power, the transmitted optical power was 13.6 W. In addition, we obtained almost constant power transmission efficiencies for all the feed light powers, averaging approximately 66.57%. As mentioned in the previous section, the O/E conversion efficiency of the PPC was 43.7%, resulting in 5.94 W of the delivered electric power in the 20 W feed light power input to the PSIC-DCF. The calculated delivered power efficiency defined as the power ratio between the feed light power input to the PSIC-DCF and the converted electric power at the RAU was approximately 30%.

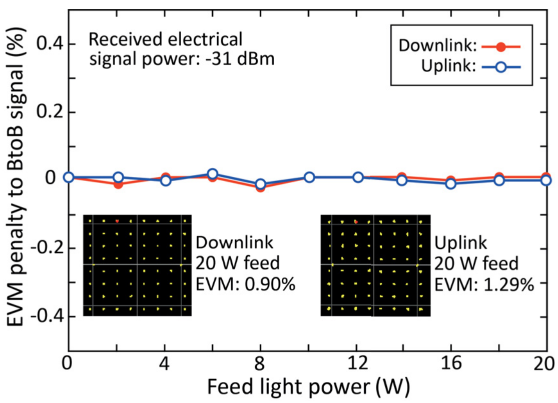


Fig.5: EVM penalties to back-to-back (BtoB) signals of downlink- and uplink-transmitted A-RoF signals. Insets show constellations of these signals.

Figure 4 shows the error-vector magnitude (EVM) characteristics of the (a) downlink- and (b) uplink-transmitted A-RoF signals. In both cases, the EVM value decreased as the received electrical signal power increased, and became constant above –40 dBm. This result indicates that nearly the same EVM characteristics are obtained with or without the feed light input. On the other hand, the constant EVM value for the uplink transmission was observed to be approximately 0.4% higher than that for the downlink transmission. As shown in Fig. 1, this penalty was caused by the fact that a EDFA was installed on the CO side for the uplink transmission and the signal was amplified after transmission.

Figure 5 shows the EVM penalties to the back-to-back signals of the downlink- and uplink-transmitted A-RoF signals while changing the feed light power input to the PSIC-DCF. In all the measurements, the received electrical signal power was set to –31 dBm. In the downlink and uplink transmissions, the penalties were almost constant and had the variations of less than 0.04% even if the feed light power was increased up to 20 W. The insets show the constellations of the signals. In the 20 W feed light input to the PSIC-DCF, good constellation maps were observed. This means that the high-power feed light does not affect the transmission characteristics of the downlink and uplink A-RoF signals in the PWoF transmission using the PSIC-DCF.

Conclusions

We demonstrated PWoF using a PSIC-DCF, which had a much smaller transmission loss than that of conventional DCFs at 976 nm. We achieved good transmission characteristics of the downlink and uplink A-RoF signals with electric power delivery of 5.94 W. The results are useful not only for simplifying link configuration, but also for extending transmission distance for PWoF capable of high-power supply using a single optical fiber.

ISBN: 978-3-8007-6426-6

Acknowledgements
This work was supported in part by the National Institute of Information and Communications Technology (NICT) (22402) in Japan and National Science Foundation (NSF) in USA through grants 2210343 and 2210344.

References

[1] I. A. Alimi, A. L. Teixeira, and P. P. Monteiro, "Toward an efficient C-RAN optical fronthaul for the future networks: A tutorial on technologies, requirements, challenges, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 708-769, 2018, DOI: 10.1109/COMST.2017.2773462

[2] C. Lim, Y. Tian, C. Ranaweera, T. A. Nirmalathas, E. Wong, and K.-L. Lee, "Evolution of radio-over-fiber technology," *J. Lightwave Technol.*, vol. 37, no. 6, pp. 1647-1656, 2019, DOI: 10.1109/JLT.2018.2876722

[3] M. Matsuura, "Recent advancement on power-over-fiber technologies," Photonics, vo. 8, no. 8, 2022, Art. No. 8080335, DOI: 10.3390/photonics8080335

[4] M. Matsuura and J. Sato, "Bidirectional radio-over-fiber systems using double-clad fibers for optically powered remote antenna units," *IEEE Photon. J.*, vol. 7, no. 1, 2015, Art. No. 7900609, DOI: 10.1109/JPHOT.2014.2381669

[5] D. Kamiyama, A. Yoneyama, and M. Matsuura, "Multichannel data signals and power transmission by power-over-fiber using a double-clad fiber," IEEE Photon. Technol. Lett., vol. 30, no. 7, pp. 646-649, 2018, DOI: 10.1109/LPT.2018.2810158

[6] M. Matsuura, N. Tajima, H. Nomoto, and D. Kamiyama, "150-W power-over-fiber using double-clad fibers," *J. Lightwave Technol.*, vol. 38, no. 2, pp. 401-408, 2020, DOI: 10.1109/JLT.2019.2948777

[7] M. Matsuura, H. Nomoto, H. Mamiya, T. Higuchi, D. Masson, and S. Fafard, "Over 40-W electric power and optical data transmission using an optical fiber," *IEEE Trans. Power Electron.*, vol. 36, no. 4, pp. 4532-4539, 2021, DOI: 10.1109/TPEL.2020.3027551

[8] M. Matsuura, "Power-over-fiber using double-clad fibers," *J. Lightwave Technol.*, vol. 40, no. 10, pp. 3187-3196, 2022, DOI: 10.1109/JLT.2022.3164566

[9] E. Erbayat, S. Petale, S. Lin, M. Matsuura, H. Hasegawa, S. Subramaniam, "Fronthaul network architecture and design for optically powered passive optical networks," in *Proc. IEEE International Conference on Communications (ICC 2024)*, Denver, US, June, 2024.

[10] S. Fafard, F. Proulx, M. C. A. York, L. S. Richard, P. O. Provost, R. Ares, V. Aimez, and D. P. Masson, "Ultrahigh efficiencies in vertical epitaxial heterostructure architectures," *Appl. Phys. Lett.*, vol. 108, no. 7, 2016, Art. No. 071101, DOI: 10.1063/1.4941240

[11] S. Fafard and D. Masson, "Perspective on photovoltaic optical power converters," *J. Appl. Phys.*, vol. 130, no. 16, 2021, Art. No. 160901, DOI: 10.1063/5.0070860

