applied sciences

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High-Performance Microwave Photonic Transmission Enabled by an Adapter for Fundamental Mode in MMFs

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Abstract: Microwave photonic links (MPLs) have long been considered as an excellent way for radio frequency (RF) transmission due to their advantages such as light weight, high bandwidth, low cost and large spurious-free dynamic range (SFDR). However, the effective mode-field area (A_{eff}) of the single-mode fiber (SMF) used in the traditional MPL is not large, so the MPL based on SMF have relatively strong nonlinearity, which limits the processing power of SMFs to a level of few milliwatts. Few-mode fibers (FMFs) have been applied in MPL as an alternative due to the larger A_{eff}, and photonic lanterns are used simultaneously to excite the high-order mode of FMFs for RF signal transmission. However, the photonic lantern could bring additional insertion loss, and the production cost of FMFs is high, so we propose an MPL based on multimode fibers (MMFs) with mode field adapters (MFAs). Since MMFs have larger A_{eff}, the nonlinearity of the link can be greatly reduced. And matched MFAs realized by reverse tapering, to excite only the fundamental mode in MMFs to reduce the crosstalk, which are very stable. As a result, the stimulated Brillouin scattering threshold and SFDR are improved by 5 dB and 14.5 dB, respectively.

Keywords: microwave photonic link; mode field adapter; reverse tapering

Citation: Wang, Y.; Yang, L.; Yang, Z.; Liu, Y.; Huang, Z.; Zhang, L. High-Performance Microwave Photonic Transmission Enabled by an Adapter for Fundamental Mode in MMFs. *Appl. Sci.* **2023**, *13*, 1794. https://doi.org/10.3390/app13031794

Academic Editor: Chi-Wai Chow

Received: 21 December 2022
Revised: 22 January 2023
Accepted: 29 January 2023
Published: 30 January 2023

1. Introduction

A microwave photonic link (MPL) works by modulating the radio frequency (RF) signal containing the baseband to the optical carrier, which is then modified by several optical devices and finally down-converted at the receiver to recover the RF signals [1]. MPLs have been increasingly applied to cable TV, military radar, radio telescope and some other fields [2–5] due to their advantages like light weight, high bandwidth, low cost and large spurious-free dynamic range (SFDR) [6–9]. SFDR is one of the very important factors to reflect the performance of MPLs. Clark et al. demonstrated a promising photonic transport and digital receiver technique for analog RF signals and proposed direct demodulation to obtain an extremely high SFDR [10]. Zheng R. et al. demonstrated a long-haul MPL achieved high SFDR by biasing the modulator at single-sideband suppressed carrier modulation and adjusting the polarization of the light entering the polarizer [1]. The stimulated Brillouin scattering (SBS) in fibers tend to limit the processing power of single-mode fibers (SMFs) to the level of milliwatts compared to high-power lasers and photodetectors that can operate with an optical power of watt-level. Therefore, the nonlinear effects of optical fibers become the bottleneck for improving the performance of MPLs. In recent years, more attention has been focused on the transmission media, that is, the fiber used in MPLs. According to fiber nonlinear theory [11], the larger the effective mode area, the weaker the nonlinear effect. Wen et al. used a higher-order mode (HOM) of few-mode fibers (FMFs) to transmit RF signals, and its large mode area helps reduce nonlinearity and improve SFDR [12], in which a photonic lantern is used to excite the corresponding modes. However, photonic lanterns are sensitive to external environment changes such as temperature or placement posture, so a specific fiber mode would not be purely excited, leading to non-negligible multi-path interference (MPI). Besides, considering the availability and cost of FMFs and mode converters, we need to seek a more stable and cost-effective solution.

Here, we propose a new MPL utilizing commercial multimode fibers (MMFs), which is featured by mode field adapters (MFAs) fabricated using reverse tapering technique and fused to both the ends of an MMF. RF signals are carried only by the fundamental mode, with greatly reduced loss and crosstalk between modes, which would significantly reduce the MPI and improve the system stability. Compared with traditional SMF-based MPLs, the SBS threshold of the MFA-based 17.6-km MMF link is improved by 5 dB, while the SFDR increases by 14.5 dB, with an input optical power of 17 dBm.

In this paper, we first introduce the background and application fields of our work and propose the novel MPL solution. Section 2 presents the principle of the proposed scheme and the fabrication of the MFAs. Section 3 shows experiments on the measurements of SBS threshold and SFDR, and the corresponding result analysis. Section 4 is the conclusion and outlook.

2. MFA Fabrication

The experimental setup for the proposed MMF-based MPL is shown in Figure 1. A light wave emitted by a 1550-nm laser is modulated by two tones (1.9 GHz and 2 GHz) that generated by arbitrary waveform generator (AWG) using an intensity modulator (MOD). The power of RF signals is attenuated by an RF attenuator (RF Att), for making the output power of the fundamental frequency (FF) signal and the third-order intermodulation (IMD3) present an approximately linear relationship with the input power. The light wave that has been modulated is amplified by an erbium-doped fiber amplifier (EDFA) then launched into a 17.6-km-long OM3 MMF via an optical circulator, and finally the Brillouin backscattering light power can be measured by the power meter. Besides, the variable optical attenuator (VOA) is used to adjust the incident optical power. Two fabricated MFAs were fused to the two ends of the MMF to excite and filter only the fundamental mode of the MMF. At the end of the link, a photodetector (PD) and an electrical spectrum analyzer (ESA) are applied to detect and analyze the output signal.

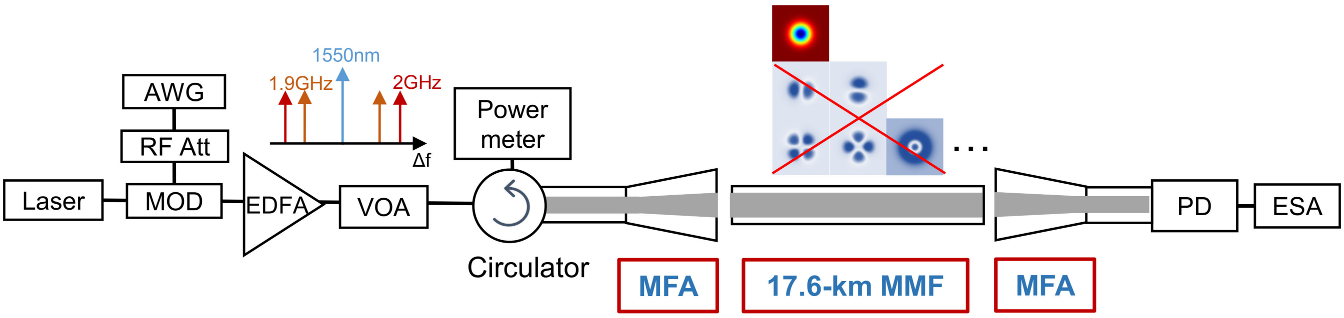

Figure 1. Schematic diagram of the microwave photonic transmission link using an MMF (OM3) with two mode field adapters, in which the large-area fundamental mode can be clearly excited.

The OM3 fibers, which are widely used in fiber communication, have a 14.5-μm mode-field diameter for the fundamental mode [13], and the A_{eff} is about 165 μm^2. As we can see, we need carefully fabricate MFAs to match the mode field of SMF and MMF. To reduce MPI, we need to expand the core of the MFA to ~14.5 μm. We plan to use reverse tapering to fabricate the MFAs by LZM-100, an optical fiber splicer produced by Fujikura. The fiber splicer uses a CO_2 laser, which makes the heating processes highly reproducible and stable. The reverse tapering process can be realized by programming, allowing any fibers to be tapered with high precision [14]. The SMF can be thickened smoothly and slowly then form a plat thickened area using the optical splicer. After that, the MFA is fabricated by cutting off at the thickened area and fusing with the MMF in alignment. We conducted six times of reverse tapering and the cross-sectional images of the MFAs are shown in

Figure 2a. The side view of the MFA obtained after the 6-th reverse tapering, which is the best match, is presented in Figure 2b. The fiber was thickened slowly from right to left. Two MFAs were fused to the two ends of the MMF, and the losses of them are 0.34 dB and 1.68 dB, respectively.

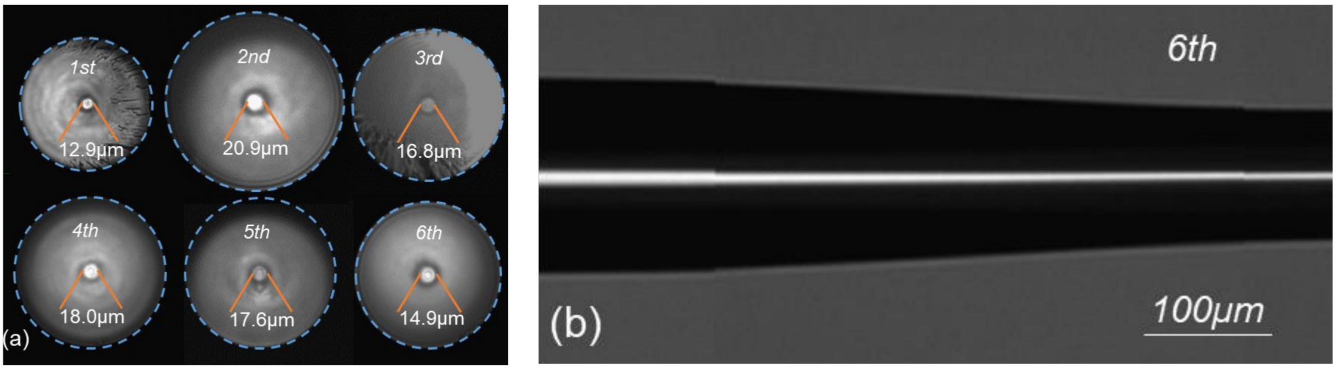

Figure 2. (**a**) The cross-sectional images of the MFAs obtained through six iterations of the reverse tapering technique, among which the 6th sample's mode field diameter can match that of the fundamental mode in the OM3 fiber. (**b**) The side view of the MFA, thickened slowly and smoothly from right to left.

3. Experimental Measurement and RF Transmission Performance

Figure 3a,b demonstrate the performances of the MMF-based MPL that we discussed above, in comparison with a G.652D SMF MPL. In order to verify whether a larger mode field area can indeed lead to lower nonlinear effects and whether the length of fiber can influence nonlinearity, we design two sets of experiments for the SBS threshold measurement. In the first set, the lengths of SMF and MMF are 10 km and 8.8 km respectively, because the SBS fluctuations are generally not significant within 2 km, while in the second set, fiber lengths are increased to 16.5 km and 17.6 km, respectively. According to the existing fibers in our lab, we chose a 17.6-km MMF for the experiment, the length of which is already in the range of typical MPLs. Besides, the characteristics of the SMF and the MMF used in the experiments are presented in Table 1 [15].

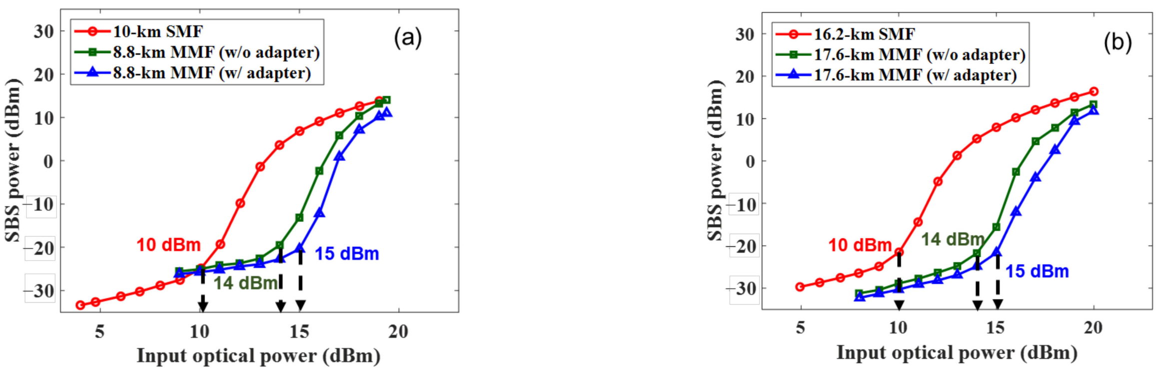

Figure 3. The back-scattered optical power versus input optical power for (**a**) a 10-km SMF and an 8.8-km MMF and (**b**) a 16.2-km SMF and 17.6-km MMF with and without adapters.

Table 1. The performance characteristics of the SMF and OM3 MMF.

Parameters	Value
α_{MMF_LP01}	0.220 dB/km
α_{SMF}	0.187 dB/km
A_{eff} of MMF_LP$_{01}$	165 μm^2
A_{eff} of SMF	80 μm^2

It can be seen that the SBS threshold of SMFs is only ~10 dBm, while that of MMFs is ~15 dBm. In addition, the SBS threshold without MFAs is 14 dBm, which is slightly smaller, indicating that the existence of the MFAs increases the SBS threshold by ~1 dB. We also prove that the SBS threshold of longer fibers is almost unchanged, no matter SMFs or MMFs. However, the back-scattered light power of the longer SMF becomes exactly stronger, while that of the longer MMF increases less, proving that it is feasible to use MMFs to improve the nonlinearity. The crosstalk of the link without MFAs is very high because the HOM components of the MMF could be excited in a high proportion, which means that the quality of the baseband signal would be severely affected.

Figure 4a demonstrates the relation of the output and input optical power of the link. When the input light power is 17 dBm, an increase of 3.8 dB can be obtained using MMFs compared to using SMFs. From Figure 4a, it can be seen that the transmitted power still increases after the incident optical power exceeds the SBS threshold, but not as fast as it is when below the SBS threshold, due to the presence of the Kerr effect in the fiber nonlinearity, where the power in the optical carrier is transferred to the sideband due to self-phase modulation and four-wave mixing (FWM). If the power in the sideband is below the SBS threshold, it continues to grow even though the optical carrier power is no longer growing due to exceeding the SBS threshold.

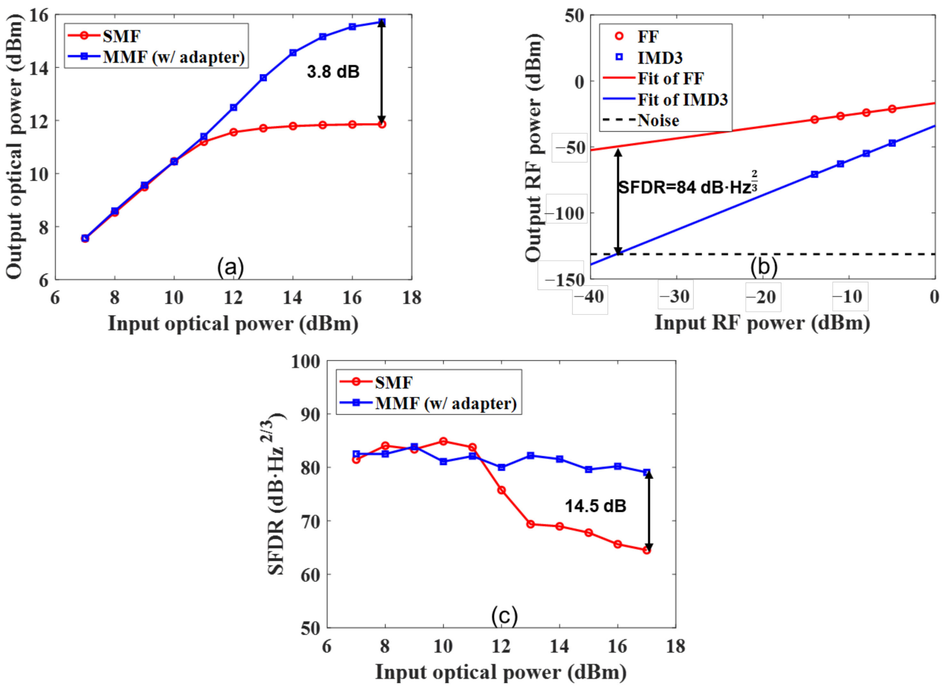

Figure 4. (**a**) The output optical power vs. input optical power. (**b**) Detected FF and IMD3 powers in SMF photonic links when input optical power is 8 dBm, as an example of measuring SFDR. (**c**) SFDR vs. input optical power.

The SFDR can be measured based on the signal output received by the ESA, which is shown in Figure 4b. The input dual-frequency RF signal can generate other frequency signals besides the fundamental frequency (FF) f_1 and f_2 due to link nonlinearity, among which the third-order intermodulation (IMD3) terms $2f_1 - f_2$ and $2f_2 - f_1$ are closest to the FF, which have a serious impact on the system. The FF and the IMD3 power values are measured a sufficient number of times at different input radio frequency (RF) signal powers and fitted to lines. The difference between the power value of FF and the noise floor is considered to be SFDR, in which the power value is obtained from the FF line based on the horizontal coordinate of the intersection of the IMD3 line and the noise floor. The formula for SFDR calculation is $\frac{2}{3}(OIP_3 - NF)$, in which OIP_3 is the intersection of the FF and IMD3 lines and NF stands for noise floor [16,17]. The IMD3 grows with the normalized optical input power and the optical spectral components that result in IMD3 include not only the optical carrier but also the modulation sidebands and FWM sidebands. Despite the large A_{eff} of the MMF and the Kerr effect is relatively weak, IMD3 in the MMF link is stronger at high input powers This is because, compared with the SMF, the MMF has a weaker SBS, which means the transmitted power can be stronger. With decreased IMD3 power and higher FF power, we obtain an improvement of 14.5-dB in SFDR based on MMFs, as presented in Figure 4c, which is measured at the input optical power of 17 dBm, a power value that is widely used in MPLs.

4. Conclusions and Discussions

We demonstrate a new method to improve the performance of microwave photonics links, that is, using MFAs fabricated by reverse tapering to match the MMF fundamental mode field, confining the signal transmitted only in the fundamental mode of MMFs. This method can effectively reduce the nonlinear effect, and the SBS threshold is 5-dB higher than that of SMFs. We also measure the SFDR of the link, and compare with the link using SMFs, there is a 14.5-dB improvement when the incident optical power is 17 dBm.

Although we have obtained the improvement on SFDR performance, the fusion of short devices like the MFA and accurate matching between the MFA and the fiber still need to be carefully improved. Besides, the MPI of the link is another subject that needs to be further investigated in the future. Even so, our work is potential to be applied in the field of high-power and long-distance RF signal transmission.

Author Contributions: Y.W. planned and wrote the paper. L.Y. participated in the experiments of the second part. Z.Y. contributed to the new idea of this work. Y.L. revised the whole manuscript and gave some valuable advice. Z.H. and L.Z. monitored the work and gave technical guidance. All co-authors participated in the review and editing job. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by National Key R&D Program of China under grant 2019YFB2203902, and National Natural Science Foundation of China (NSFC) under grant 62105241.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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