Distributed vibration sensing and simultaneous self-homodyne transmission of single-carrier net 5.36 Tb/s signal using 7-core fiber

Jianwei Tang[1,2], Xueyang Li[*1], Chen Cheng[2], Linsheng Fan[2], Yaguang Hao[1,2], Bing Yue[1], Jiali Li[1], Zhixue He[1], Yanfu Yang[*1,2], and Weisheng Hu[1]

[1]*Department of Circuits and System, Peng Cheng Laboratory (PCL), Shenzhen, China*

[2]*School of Electronics and Information Engineering, Harbin Institute of Technology (Shenzhen), Shenzhen, China*

E-mail: xueyang.li@pcl.ac.cn; yangyanfu@hit.edu.cn

Abstract: We demonstrate self-homodyne coherent transmission of a space-division multiplexed dual-pol 120-Gbaud 16 QAM signal achieving a single-carrier net data rate of 5.36 Tb/s, and simultaneously distributed vibration sensing using a 41.4 km weakly-coupled 7-core fiber.

1. Introduction

Recently, space division multiplexing (SDM) technology has attracted growing attention since it fulfills the fast-increasing bandwidth demand. Compared with conventional single-mode fiber (SMF), multi-core fiber (MCF) has the potential to overcome the capacity limit due to high spatial multiplicity [1,2]. Among various MCF types, the weakly-coupled (WC) MCF is a promising candidate for early commercial deployment because of independent spatial channels having marginal crosstalk that removes the complexity resulting from high-order multiple-input multiple-output (MIMO) equalization.

Introducing sensing capability into SDM communication systems provides the opportunity to enable new applications such as environmental monitoring and early disaster warning. Prior work has demonstrated SDM transmission systems with integrated distributed acoustic sensing (DAS) based on the Rayleigh backscatter. The spectral efficiency per fiber is compromised since a dedicated fiber core is required for the transmission of sensing pulses. Furthermore, backscatter-based distributed fiber optical sensing has a short sensing range and low compatibility with the existing fiber telecom infrastructure equipped with isolators in amplifier modules [3,4]. In comparison, forward vibration sensing based on phase detection offers extended sensing reach and has been validated *in deployed SMF* by correlating the phase retrieved from two counter-propagating continuous wave (CW) carriers or communication signals [5,6]. Recently, high-speed and scalable self-homodyne coherent transmission systems based on WC-MCF have been demonstrated possessing reduced signal processing complexity due to the removal of carrier phase recovery [7]. It would be beneficial to develop a compatible and low-complexity approach for integrating the distributed vibration sensing functionality into high-capacity self-homodyne SDM transmission systems without requiring a dedicated fiber core for the sensing signal.

In this paper, we propose a low-complexity forward vibration sensing scheme that is compatible with self-homodyne transmission system based on WC-MCF. In a self-homodyne SDM system architecture, we sent a local oscillator (LO) in the central core of a WC 7-core fiber. This core is shared by a low-power counter-propagating CW sensing carrier, which together with the LO allows phase detection-based vibration sensing and demonstrates measurement of the applied vibration signal along with accurate localization of the vibration source. In the meantime, we transmit a single-carrier net 5.36 Tb/s optical signal over a 41.4 km of WC 7-core fiber without performing carrier frequency and phase recovery.

2. Principle

In Fig. 1(a), the schematic of our proposed scheme and the cross-section of WC 7-core fiber are shown. The six outer cores are dedicated to transmitting the telecom signals for communication, while the central core of WC 7-core fiber transmits the LO (CW1) for self-homodyne coherent detection (SHCD), and a counter-propagating CW carrier (CW2) is also injected in the central core sharing with CW1 to enable distributed vibration sensing. When external vibration occurs at position Z, the phase disturbance of CW1 continues to propagate a fiber distance of L-Z, while the CW2 propagates over a fiber length of Z. After timing synchronization between two receivers, for example, through GPS, the vibration location can be calculated by the following Eq. (1), where Δt is the time delay between the phase of CW1 and CW2, c is the speed of light and n stands for the refractive index of fiber.

$$Z = \frac{L}{2} - \frac{\Delta t \cdot c}{2n} \tag{1}$$

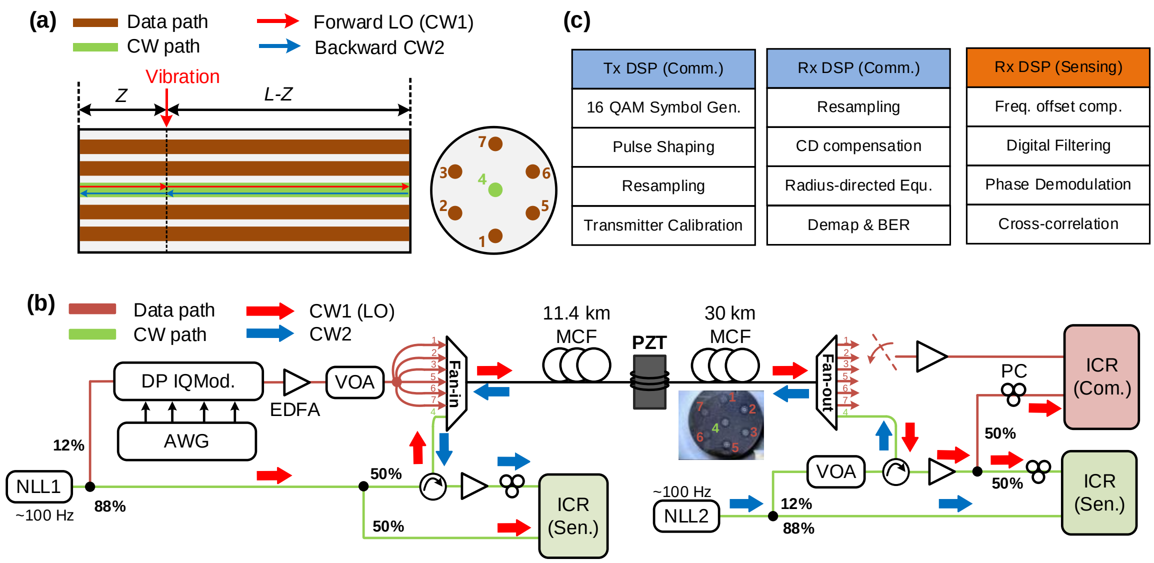

Fig.1. (a) Schematic of the proposed integrated sensing and communication system and the cross-section of WC 7-core fiber. (b) Experimental setup. (c) Tx and Rx DSP blocks for communication signal, respectively, and Rx DSP for sensing signal.

2. Experimental setup

Fig. 1(b-c) shows the experimental setup and DSP blocks. At the transmitter, an arbitrary waveform generator (AWG, Keysight 8199A) produces 4 lanes of RF signals that are fed to a dual-polarization (DP) IQ modulator with co-packaged driver amplifiers. This modulator imprints a 120 Gbaud DP-16QAM signal onto an optical carrier at 1550 nm that is split from a narrow linewidth laser (NLL1, NKT X15). The rest of the optical power of NLL1 is equally divided into two parts. One part serves as the co-propagating local oscillator (CW1) in the central core (core 4) of the MCF as required for self-homodyne coherent detection (SHCD) of the telecom signals, while the other part beats with the counter-propagating sensing carrier (CW2) from NLL2 sharing the same core in order to realize phase-based vibration detection. We note that NLL2 has a frequency offset of ~15 MHz relative to NLL1. The modulated signal is amplified by an Erbium-doped fiber amplifier (EDFA), and then split into six branches by a power splitter and separately coupled into the six outer cores of the WC 7-core fiber. The measured inter-core crosstalk is below -40 dB, ensuring marginal interference between the CW carriers and telecom signals. To introduce external vibration, a short section of WC 7-core fiber during transmission is wrapped around a piezoelectric transducer (PZT), and a periodic burst oscillation signal is applied to the PZT.

At the receiver, the continuous wave (CW1) transmitted through core 4 is amplified and split into two equal parts, serving as the LO for SHCD and forward CW sensing signal, respectively. The telecom signals in the outer 6 cores are received by an integrated coherent receiver (ICR) after amplification and then sampled by a 256 GS/s real-time oscilloscope (RTO, Keysight UXR0594AP) for offline processing. We couple 12% of optical power of NLL2 back into core 4 via a circulator and optimize the optical power via a variable optical attenuator (VOA) to minimize the impact of Rayleigh scattering on the LO for SHCD. The remaining 88% optical power of NLL2 is used as the LO for heterodyne coherent detection of the forward CW sensing signal (CW1). The DSP blocks implemented to process the communication and sensing signals are illustrated in Fig. 1(c) Frequency offset compensation and carrier phase recovery are eliminated due to SHCD, whereas cross-correlation between the phases of CW1 and CW2 sharing the same fiber core allows low-complexity vibration detection and localization.

3. Results and Discussions

Due to the Rayleigh backscattering induced by CW2, we first assess the change in the communication performance by variating the power of the counter-propagating CW2. We depict in Fig. 2(a) the BER of a DP-120Gbaud-16QAM signal as a function of the launch power of CW2. At a launch power below 0 dBm, the influence of the Rayleigh backscatter from CW2 on the telecom signal is minimal. However, at a high launch power of 9 dBm, we observe a significant BER degradation as shown in this figure. Thus, we set a low launch power of -8 dBm for the counter-propagating sensing carrier CW2. Fig. 2(b) shows the electrical spectra of the 16 QAM signals with or without turning on CW2 at the chosen launch power, showing marginal spectral change at a sufficiently weak Rayleigh backscatter. Fig. 2(c) is the BER of the 120 Gbaud 16 QAM DP-signal traveling in the outer 6 cores of the 7-core fiber with the inset showing the constellation diagram of the signal from core 1. We achieve the transmission of 6×960 Gb/s 16 QAM signals over 41.4 km of weakly-coupled 7-core optical fiber reaching a bit error rate (BER) below the HD-FEC threshold of 3.8E-3. After removing 7% overhead, the net data rate is 5.36 Tb/s.

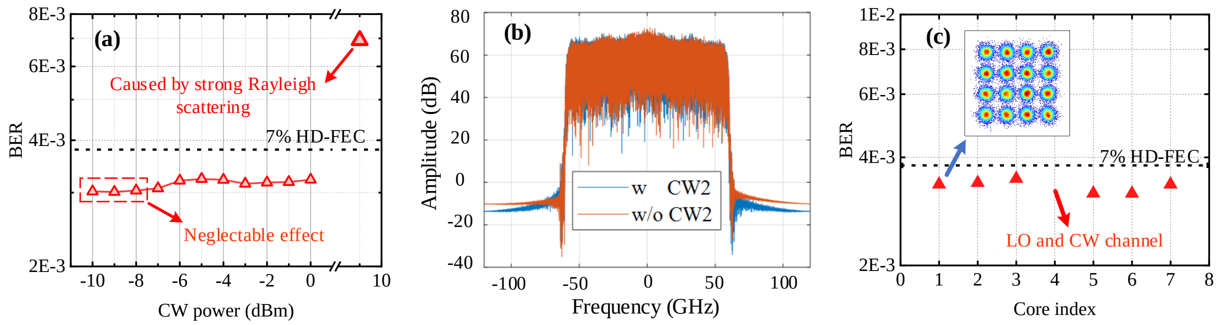

Fig.2. (a) Measured BER of 16QAM signal versus the lunch power of CW2. (b) Electrical power spectral density (PSD) with or without CW2. (c) BER of all communication signals in MCF and constellation diagram of core1.

After applying a periodic burst oscillation signal to the PZT, we retrieve the phases of CW1 (forward) and CW2 (backward) through heterodyne detection. We show the retrieved phase waveforms in Fig. 3(a) after frequency offset compensation. Subsequently, we apply a high pass filter to eliminate the out-of-band noise due to laser phase noise and environmental disturbances. The filter phase waveforms are shown in Fig. 3(b). Note that this filtering procedure eliminates the influence of slowly variating phase noises and improves the accuracy of vibration localization using cross-correlation. Fig. 3(c) shows an enlarged view of the portion enclosed by the dashed circle in Fig. 3(b), where a clear time delay between the two phase waveforms is observed. Fig. 3(d) shows the cross-correlation of the two phase signals, and the corresponding location is 11.05 km according to Eq. (1). Taking into account the EDFA, PC, circulator, and fiber patch cord in the system, the location result agrees well with the expected distance of 11.4 km measured by φ-OTDR.

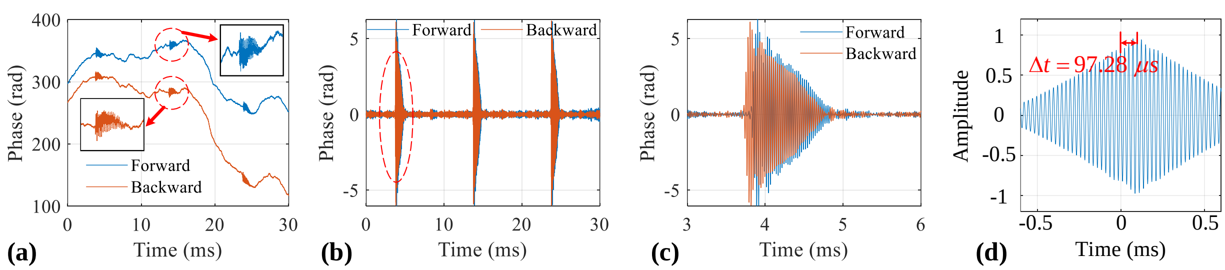

Fig.3. (a) Retrieved phase fluctuation of forward (CW1) and backward (CW2) signal. (b) Phase of CW1 and CW2 after digital filtering. (c) The details of the dotted box of (b). (d) Cross-correlation between the phase of CW1 and CW2.

4. Conclusion

We propose a low-complexity scheme to incorporate the vibration sensing capability into self-homodyne SDM transmission systems utilizing weakly-coupled MCF. Vibration sensing is enabled without degrading the high spectral efficiency offered by SDM fiber, since the same fiber core is leveraged for the forward-transmission of a remote LO and backward-transmission of a CW sensing signal. The proposed scheme enables the transmission of single-carrier net 5.36 Tb/s of DP-16QAM signal and simultaneous vibration sensing over 41.4 km of WC 7-core fiber, offering a promising approach to realizing high-speed and low-cost SDM transmission systems with integrated vibration sensing capability.

This work is supported by the National Key R&D Program of China (2020YFB1806401), the National Natural Science Foundation of China (62201308), and the Science Technology and Innovation Commission of Shenzhen Municipality (JCYJ20210324131408023).

6. References

[1] D. J. Richardson et al., Nat. Photonics, 7(4), 354-362 (2013).
[2] B. J. Puttnam et al., J. Light. Technol., 38(1), 123-130 (2020).
[3] Y. Chen et al., IEEE Commun. Mag., 61(8), 182-188 (2023).
[4] Y. Guo et al., Sci. Reports, 13(1), 15412 (2023).
[5] E. Ip et al., J. of Light. Technol., 40(5), 1472-1482 (2022).
[6] Y. Yan et al., in *2023 OFC*, paper W1J.4.
[7] T. Gui et al., J. Lightw. Technol., 39(4), 1231-1238 (2021)