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Automatic turbulence mitigation for coherent free-space optical links using crystal-based phase conjugation and fiber-coupled data modulation

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There are various performance advantages when using temporal phase-based data encoding and coherent detection with a local oscillator (LO) in free-space optical (FSO) links. However, atmospheric turbulence can cause power coupling from the Gaussian mode of the data beam to higher-order modes, resulting in significantly degraded mixing efficiency between the data beam and a Gaussian LO. Photorefractive crystal-based self-pumped phase conjugation has been previously demonstrated to "automatically" mitigate turbulence with limited-rate free-space-coupled data modulation (e.g., <1 Mbit/s). Here, we demonstrate automatic turbulence mitigation in a 2-Gbit/s quadrature-phase-shift-keying (QPSK) coherent FSO link using degenerate four-wave-mixing (DFWM)-based phase conjugation and fiber-coupled data modulation. Specifically, we counter-propagate a Gaussian probe from the receiver (Rx) to the transmitter (Tx) through turbulence. At the Tx, we generate a Gaussian beam carrying QPSK data by a fiber-coupled phase modulator. Subsequently, we create a phase conjugate data beam through a photorefractive crystal-based DFWM involving the Gaussian data beam, the turbulence-distorted probe, and a spatially filtered Gaussian copy of the probe beam. Finally, the phase conjugate beam is transmitted back to the Rx for turbulence mitigation. Compared to a coherent FSO link without mitigation, our approach shows up to ~14-dB higher LO-data mixing efficiency and achieves error vector magnitude (EVM) performance of <16% under various turbulence realizations.

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Compared to radio systems, free-space optical (FSO) links hold the promise of higher data capacity and a lower probability of intercept [1]. In addition, FSO systems also have potential advantages of wider license-free frequency spectrum and smaller size of the transmitter (Tx)/receiver (Rx) [2,3]. FSO demonstrations commonly use intensity modulation and direct detection [2,3]. However, similar to optical fiber links, there are advantages in increased receiver sensitivity and spectral efficiency by using phase-based data encoding [e.g., quadrature-phase-shift-keying (QPSK) and quadrature-amplitude-modulation (QAM)] and coherent detection with a local oscillator (LO) in an FSO link [4,5].

A key challenge in FSO communications is atmospheric turbulence [6,7]. For direct detection, this can cause power scintillations and beam wander [7,8]. The situation can be much worse for coherent detection since turbulence can cause significant power loss due to the inability to efficiently mix a fundamental Gaussian LO beam with a distorted data beam in a coherent receiver [9,10]. This inefficiency comes from the turbulence-induced coupling of power into higher-order spatial modes [9,11]. Various approaches to mitigate turbulence for coherent reception include: (a) adaptive optics by measuring the wavefront distortion and applying a digital signal processing (DSP)-calculated conjugate phase for correction [12]; and (b) multi-mode combining by collecting multiple modes and recovering their power by multiple coherent detectors and additional DSP [13–15]. However, it might be advantageous to "automatically" mitigate turbulence for efficient coherent detection using a single detector without additional DSP.

One approach for automatic mitigation is to: (i) propagate a probe beam from the Rx to the Tx through the turbulence and experience distortion; (ii) reflect the beam with a conjugate phase profile by a self-pumped photorefractive crystal [16–21]; (iii) temporally modulate the data by adding electrical voltages on the crystal [19,20] or using an external free-space coupled modulator [21]; and (iv) transmit the data beam back through the turbulence to mitigate the distortion [17,20–24]. This approach has been demonstrated with <~1-Mbit/s intensity modulation [19–21]. However, this approach is challenged by the dramatically lower bandwidth of free-space coupled modulators relative to that of fiber-coupled modulators (e.g., <1 GHz [24–26] as compared to >40 GHz, respectively [27]).

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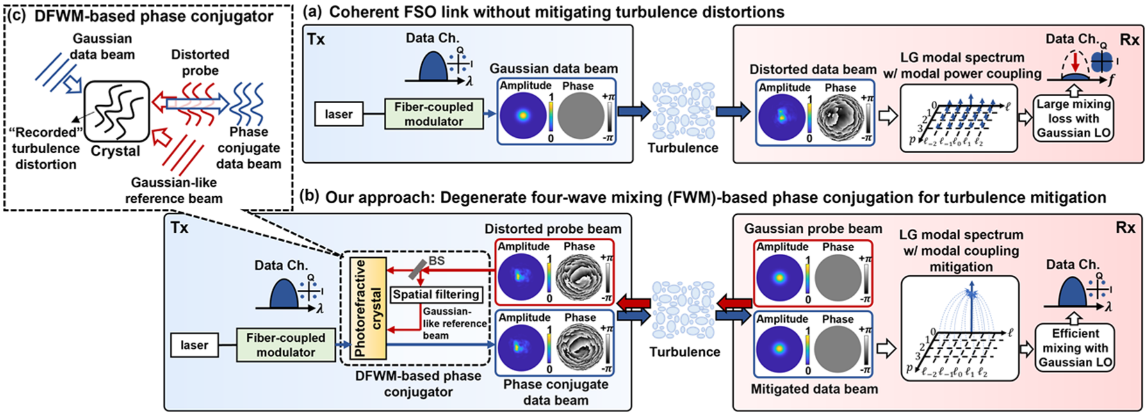

Fig. 1. (a) Coherent FSO links can be significantly degraded by turbulence-induced beam distortion and modal coupling. (b) Our approach using DFWM-based phase conjugation for automatically mitigating turbulence. (c) Detailed process of the DFWM-based phase conjugation. The distorted probe beam and a Gaussian-like reference beam interfere inside the crystal to "record" turbulence distortion. A Gaussian data beam is used to "read" the distortion and generate a phase conjugate data beam.

In this Letter, we demonstrate automatic turbulence mitigation in a 2-Gbit/s QPSK coherent FSO link using crystal-based phase conjugation and fiber-coupled data modulation. We transmit a Gaussian probe beam from the Rx to the Tx through turbulence. At the Tx, we generate a Gaussian beam carrying a QPSK data signal modulated by a fiber-coupled phase modulator. Subsequently, we create a phase-conjugated data beam through a degenerate four-wave-mixing (DFWM) nonlinear process in an Rh-reduced $KNbO_3$ crystal. When the beam propagates back through the turbulence to the Rx, turbulence-induced beam distortion and modal coupling are automatically mitigated, and efficient coherent heterodyne detection is enabled.

Figure 1(a) shows the turbulence-induced degradations for a coherent FSO link. The turbulence can distort the wavefront of the transmitted Gaussian data beam and cause significant modal coupling from the Gaussian mode [i.e., Laguerre–Gaussian (LG) mode with mode indices ℓ=0 and p=0] to other LG modes [9]. At the Rx, the multi-mode data beam cannot efficiently mix with a Gaussian LO beam, thereby inducing mixing loss and signal quality degradation.

Photorefractive crystal-based self-pumped phase conjugation has been demonstrated to mitigate turbulence [19–21]. In this approach, a Gaussian probe beam is transmitted from the Rx to the Tx. At the Tx, a phase-conjugator is used to "reflect" the probe beam and generate a phase-conjugate beam [16,17]. After phase conjugation, a free-space data modulator can be used to temporally modulate the data on the beam [21]. When the data beam propagates back through the same turbulence, turbulence-induced spatial distortion and modal power coupling are automatically mitigated [17,20–24]. However, in this approach, the free-space-based data modulation may only support a low bandwidth [19–21].

As shown in Fig. 1(b), we use DFWM-based phase conjugation [16] to mitigate turbulence. The turbulence-distorted probe beam is first divided into two copies at the Tx. One of the copies propagates through a spatial filter to remove the high-spatial-frequency components and generate a Gaussian-like reference beam [28]. The reference beam and another copy of the distorted probe beam interfere with each other inside the crystal to form a grating to "record" the spatial turbulence distortion, as shown in Fig. 1(c). At the Tx, a Gaussian data beam is first generated by a wide bandwidth, fiber-coupled modulator and propagates in a direction opposite to that of the reference beam through the crystal to "read" the distortion and generate a phase conjugate data beam. To generate high-fidelity phase conjugation, the Gaussian data beam and the reference probe beam should propagate through the crystal in a counter-propagating manner [18,20,29]. Misalignment between these two beams might induce undesired spatial intensity and phase variations on the phase conjugate beam [29], which can affect the performance of turbulence mitigation. The specific alignment requirements and performance penalties depend on the specific system parameters, and the performance can be modeled based on various published analyses [18,20,29]. The resulting phase conjugate beam then propagates through the assumingly same turbulence to the Rx.

Figure 2 shows our experimental setup. At the Rx, we generate a CW probe beam at 1064 nm, amplify it to ~800 mW by a ytterbium-doped fiber amplifier (YDFA), couple it to free space

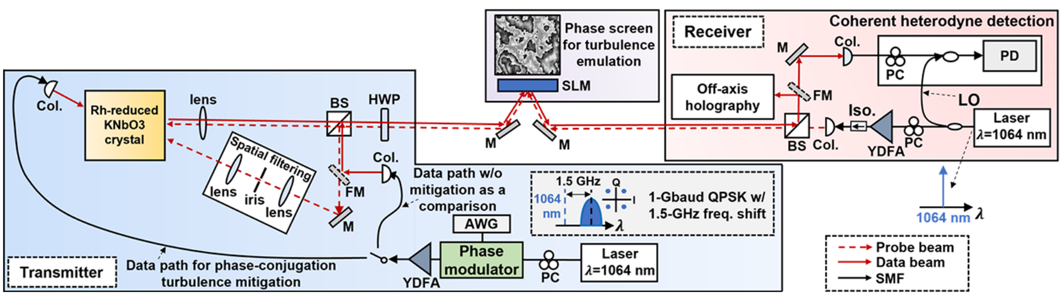

Fig. 2. Experimental setup for automatic turbulence mitigation using phase conjugation in a 2-Gbit/s QPSK coherent FSO link. AWG, arbitrary waveform generator; BS, beam splitter; Col., collimator; FM, flip mirror; HWP, half-wave plate; Iso., isolator; M, mirror; PC, polarization controller; PD, photodiode; SLM, spatial light modulator; SMF, single-mode fiber; YDFA, ytterbium-doped fiber amplifier.

as a Gaussian beam with a waist diameter of ~2.5 mm, and propagate it from the Rx to the Tx in a ~1-m free-space link. The turbulence effect is emulated by loading phase screens on an SLM placed around the middle of the link. These phase screens are designed based on Kolmogorov turbulence power spectrum statistics [7]. The strength of the turbulence is characterized by D/r_0, where D is the beam size and r_0 is the Fried turbulence parameter [7]. A larger D/r_0 results in stronger turbulence distortion [9]. When the distorted probe beam arrives at the Tx, we use a beam splitter to create its two copies, with one being spatially filtered to a Gaussian-like reference pump beam. Spatial filtering is performed by a 4*f* system consisting of two lenses with focal lengths of 30 mm and an iris with a diameter of 30 μm. The Gaussian-like reference beam and distorted probe beam cross with an angle of ~30°, and interfere inside an Rh-reduced $KNbO_3$ crystal to “record” the turbulence distortion [28]. We note that the beam size of the Gaussian data beam and the probe beam might affect the performance of turbulence mitigation. If the Gaussian data beam is too small compared to the distorted probe beam, it may not effectively overlap with the probe beam inside the crystal to “read” the turbulence distortion [28,29]. As a result, the generated phase conjugate beam carries only part of the spatial conjugation of the distortion, and the turbulence mitigation performance might be degraded [29]. In our demonstration, we use a lens to reduce the size of the probe beam to ensure good spatial overlap of the two beams [28,29]. One may also consider using a beam expander to increase the size of the Gaussian data beam to achieve an effective beam overlap.

At the Tx, we generate a Gaussian data beam carrying a 2-Gbit/s QPSK signal with a 1.5-GHz frequency offset through a fiber-coupled phase modulator. The frequency offset is used to provide a guard band for reducing signal-to-signal beating interference in heterodyne detection [9]. We propagate the Gaussian data beam in a reverse direction through the crystal to “read” the turbulence distortion and generate a phase-conjugated data beam, which then propagates back toward the Rx through the same emulated turbulence. At the Rx, after being coupled into an SMF, the data signal is mixed with an LO in a PD. The power of the LO is ~0 dBm. We measure the complex wavefront of the received data beam and perform LG modal decomposition using off-axis holography to analyze the turbulence-induced wavefront distortions [30]. Since we only have one laser at 1064 nm, we split the power of the laser for multiple uses, including generating the probe beam, the data beam, and acting as the LO.

Figure 3 shows the intensity profiles of the probe, reference, and data beams under one realization. Our results show that the mitigated beam can have a Gaussian-like profile with little turbulence distortion. In an ideal case, the phase conjugate beam should have a similar intensity profile as the distorted probe beam. However, they show some differences in our results. This might be due to the imperfect reference beam generation.

We measure the beam profiles and LG modal spectra of the received data beam without and with phase-conjugation mitigation in Figs. 4(a) and 4(b), respectively. We note that, for the phase conjugate beam generation through the crystal, the conversion efficiency from the input Gaussian data beam to the output phase conjugate data beam is measured to be approximately −20 dB without turbulence. With turbulence, the efficiency can be decreased, which might be due to a larger loss during the reference beam generation through spatial filtering [28] (e.g., ~5-dB power reduction for the turbulence realization of D/r_0~6). To focus on the turbulence mitigation performance,

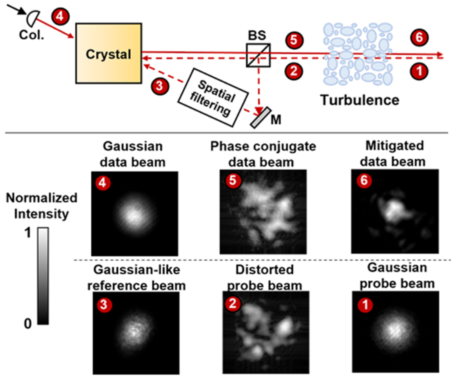

Fig. 3. Measured intensity profiles of the probe, reference, and data beams under one turbulence realization (D/r_0~4).

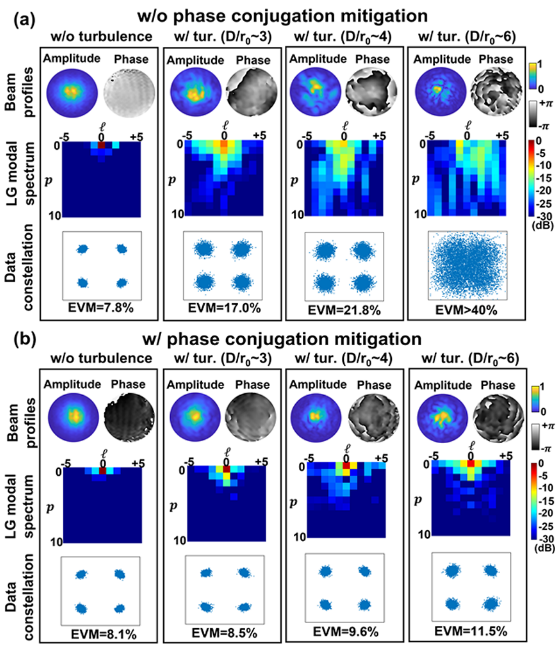

Fig. 4. Beam profiles, modal spectra, and recovered data constellations of the received data beam.

we keep the same optical power (~4 mW) of the transmitted Gaussian (w/o mitigation) and phase conjugate (w/ mitigation) data beam. Our results show that without mitigation, the received data beam becomes more distorted and experiences stronger modal coupling effects under a stronger turbulence distortion. For the turbulence realization with a D/r_0~6, ~18-dB power loss is observed in the fundamental Gaussian mode. Due to the modal power coupling and inefficient mixing with the LO, the quality of the received QPSK signal is significantly degraded with increased turbulence strength [e.g., error vector magnitude (EVM) [31] increases from ~8% to >40%]. However, with the phase conjugation mitigation, the beam distortion and modal power coupling effect are largely mitigated with up to ~14-dB improvement (e.g., <−4 dB for D/r_0~6). As a result, the EVMs of <12% can be achieved under a strong turbulence case.

As shown in Fig. 5, with mitigation, the average LO-data mixing loss can be reduced by 5.4 dB and 12.6 dB for the weaker and stronger turbulence, respectively. As a result, with mitigation, EVMs are achieved under ~16%, while without mitigation,

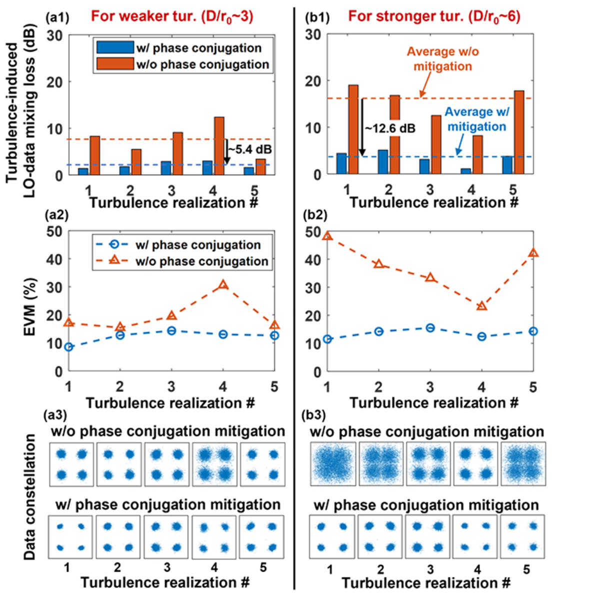

Fig. 5. (a1) and (b1) Turbulence-induced LO-data mixing loss, (a2) and (b2) EVMs, and (a3) and (b3) data constellations.

the EVMs can be >30% and >40% for the weaker and stronger turbulence, respectively. The data constellations in Figs. 5(a3)–5(b3) indicate that the quality of recovered QPSK data can be significantly improved.

For our experiment, the transmission distance was ∼1 meter. However, for an FSO link over much longer distances, there can be significant misalignment effects [32]. Such effects might be induced by beam wandering and pointing errors resulting from the longer absolute distance and atmospheric effects [32]. As an example, a misaligned beam may not be coupled into the crystal with an appropriate incident angle for the efficient generation of a phase conjugate beam [20,29]. We believe that such misalignment effect might be mitigated by using accurate and dynamic beam tracking techniques to maintain a proper incident angle on the crystal [33].

Our demonstration is for 1064 nm, which is mainly due to the working wavelength of our crystal [28]. However, we think our system architecture can be potentially applied to other wavelengths given that other appropriate photorefractive crystals can be used [34–36]. One potential example might be using proton-implanted Fe-doped $KNbO_3$ for ∼1550 nm [34]. Moreover, the response time of our crystal is ∼2 minutes, which is much slower than the real dynamic turbulence changes (e.g., ∼1 kHz) [7]. However, the performance of our system can potentially be improved by using faster crystals. Some crystals have been reported to support a less than millisecond refresh rate in the visible wavelength region [35,36], which might enable real-time turbulence mitigation.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

REFERENCE

1. M. A. Khalighi and M. Uysal, IEEE Commun. Surv. Tutorials **16**, 2231 (2014).
2. H. Kaushal and G. Kaddoum, IEEE Commun. Surv. Tutorials **19**, 57 (2017).
3. H. Hemmati, *Near-Earth Laser Communications*, 2nd ed.(CRC Press, 2021).
4. G. Li, Adv. Opt. Photonics **1**, 279 (2009).
5. K. Kikuchi, J. Lightwave Technol. **34**, 157 (2016).
6. R. J. Noll, J. Opt. Soc. Am. **66**, 207 (1976).
7. L. C. Andrews and R. L. Phillips, *Laser Beam Propagation Through Random Media*, 2nd Edition (SPIE Press, 2005).
8. H. Yuksel, S. Milner, and C. Davis, J. Opt. Netw. **4**, 462 (2005).
9. R. Zhang, N. Hu, H. Zhou, K. Zou, X. Su, Y. Zhou, H. Song, K. Pang, H. Song, A. Minoofar, Z. Zhao, C. Liu, K. Manukyan, A. Almaiman, B. Lynn, R. W. Boyd, M. Tur, and A. E. Willner, Nat. Photonics **15**, 743 (2021).
10. Y. Ren, A. Dang, L. Liu, and H. Guo, Appl. Opt. **51**, 7246 (2012).
11. B. Rodenburg, M. P. Lavery, M. Malik, M. N. O'Sullivan, M. Mirhosseini, D. J. Robertson, M. Padgett, and R. W. Boyd, Opt. Lett. **37**, 3735 (2012).
12. M. Chen, C. Liu, D. Rui, and H. Xian, Opt. Commun. **434**, 91 (2019).
13. N. K. Fontaine, R. Ryf, and Y. Zhang, *et al.*, in *45th European Conference on Optical Communication (ECOC 2019)* (IET, 2019), pp. 1–4.
14. M. Arikawa and T. Ito, Opt. Express **26**, 28263 (2018).
15. D. J. Geisler, T. M. Yarnall, M. L. Stevens, C. M. Schieler, B. S. Robinson, and S. A. Hamilton, Opt. Express **24**, 12661 (2016).
16. R. A. Fisher, *Optical Phase Conjugation* (Academic press, 2012).
17. J. Feinberg, Opt. Lett. **7**, 486 (1982).
18. R. W. Boyd, *Nonlinear Optics* (Academic press, 2020).
19. D. M. Pepper, Appl. Phys. Lett. **49**, 1001 (1986).
20. D. M. Pepper, D. A. Rockwell, and G. J. Dunning, IEEE Circuits Devices Mag. **7**, 21 (1991).
21. C. Medrano, M. Zgonik, P. Bernasconi, and P. Günter, Opt. Commun. **128**, 177 (1996).
22. T. Honda and H. Matsumoto, J. Opt. Soc. Am. B **11**, 1983 (1994).
23. R. Lind and G. Dunning, in *Conference on Lasers and Electro-Optics* (Optica Publishing Group, 1983), paper THC5.
24. J. Chen, Z. Yu, T. Wang, Z. Liu, and S. Gao, Opt. Commun. **507**, 127629 (2022).
25. I.-C. Benea-Chelmus, S. Mason, M. L. Meretska, D. L. Elder, D. Kazakov, A. Shams-Ansari, L. R. Dalton, and F. Capasso, Nat. Commun. **13**, 3170 (2022).
26. T. Mikaelian, M. Weel, A. Kumarakrishnan, P. R. Battle, and R. C. Swanson, in *Proceedings, IEEE Aerospace Conference* (IEEE, 2002), Vol. 3, pp. 3-1487–3-1492.
27. D. Zhu, L. Shao, M. Yu, R. Cheng, B. Desiatov, C. J. Xin, Y. Hu, J. Holzgrafe, S. Ghosh, A. Shams-Ansari, E. Puma, N. Sinclair, C. Reimer, M. Zhang, and M. Lončar, Adv. Opt. Photonics **13**, 242 (2021).
28. A. Brignon, J.-P. Huignard, M. H. Garrett, and I. Mnushkina, Appl. Opt. **36**, 7788 (1997).
29. G. S. He, Prog. Quantum Electron. **26**, 131 (2002).
30. Y. Zhou, J. Zhao, B. Braverman, K. Pang, R. Zhang, A. E. Willner, Z. Shi, and R. W. Boyd, Phys. Rev. Appl. **15**, 034011 (2021).
31. R. Schmogrow, B. Nebendahl, M. Winter, A. Josten, D. Hillerkuss, S. Koenig, J. Meyer, M. Dreschmann, M. Huebner, C. Koos, J. Becker, W. Freude, and J. Leuthold, IEEE Photonics Technol. Lett. **24**, 61 (2012).
32. H. G. Sandalidis, T. A. Tsiftsis, and G. K. Karagiannidis, J. Lightwave Technol. **27**, 4440 (2009).
33. H. Kaushal, V. Jain, and S. Kar, *Free Space Optical Communication* (Springer, 2017).
34. S. Brülisauer, D. Fluck, P. Günter, L. Beckers, and C. Buchal, J. Opt. Soc. Am. B **13**, 2544 (1996).
35. A. A. Kamshilin and V. V. Prokofiev, Opt. Lett. **27**, 1711 (2002).
36. E. Voit, M. Zha, P. Amrhein, and P. Günter, Appl. Phys. Lett. **51**, 2079 (1987).