Entanglement Assisted Radars Operated over Strong Atmospheric Turbulence Channels

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ABSTRACT
In this invited paper we review our recent research activities on experimental demonstration of entanglement based (EB) radars, operated over strong atmospheric turbulence channels. In conventional EB communications, sensing, and radars the phase-conjugation, required before homodyne detection takes place, is performed on received signal photons. In atmospheric turbulent channels, the signal photons are affected by diffraction, absorption, scattering, and atmospheric turbulence effects so that only limited number of weak target probe returned signal photons reach the receiver side in EB radars. Moreover, it is extremely difficult to perform any phase-conjugation on weak signal photons when the average number of received photons is <<1. To solve this problem, we have recently proposed to perform phase-conjugation on bright idler photons instead. Namely, we perform the wavelength conversion by the PPLN waveguide on bright idler photons, so that the idler photons will have the same wavelength as the signal photons, and after that we use a classical homodyne balanced detector as an entanglement assisted detector. To generate entangled photon pairs, we use C-/L-band tunable laser, EDFA, the PPLN waveguide, and WDM demultiplexers. To demonstrate the high-potential of the proposed EB radar concept, we developed an experimental outdoor free-space optical (FSO) testbed at the University of Arizona campus. Using this FSO testbed we experimentally demonstrate that the proposed EB radar significantly outperforms the corresponding classical counterpart and can operate in strong turbulence regime. To improve the detection probabilities further, we use deformable mirror-based adaptive optics.
Keywords: Entanglement, radars, quantum sensing, quantum radars, entanglement assisted detection.

1. INTRODUCTION

The entanglement brings several key advantages over classical approaches [1]-[9]. It enables beating the classical channel capacity [1] in highly noisy and lossy regime, beating classical sensor sensitivity [1], achieving unconditional security guaranteed by the quantum information theorems [1],[8],[9]; outperforming classical radars [1],[5]-[7] to mention few. Key idea behind the research related to the quantum radars is to overcome the quantum limit of classical radars [1]-[7],[10],[11]. Compared to classical radars, quantum radars are more difficult to implement. Nevertheless, there are several relevant advantages of quantum radars such as higher target detection probability in a low signal-to-noise ratio (SNR) regime, better receiver sensitivity, better quality of synthetic-aperture radar imaging, better resilience to jamming; and higher cross-section area [11]. Popular quantum radar techniques include: quantum radars based on quantum illumination concept [10] and the interferometric radar [1],[11].

In this invited paper, we describe our recent experimental demonstrations on entanglement based radars outperforming the classical radars over strong atmospheric turbulence channels [1],[2]. In conventional entanglement based communications, sensing, and radars studies the phase-conjugation step is performed on received signal photons. When signal photons are transmitted over atmospheric turbulent channels, their propagation is affected by various effects including diffraction, absorption, scattering, and atmospheric turbulence. In particular, in entanglement based radars, when atmospheric turbulence effects are strong only a small number of target probe returned weak signal photons eventually reach the receiver side. When the average number of received photons is <<1 it is extremely difficult to perform the phase-conjugation. To solve this problem, we proposed in [2],[3] to perform instead the phase-conjugation on bright idler photons. By performing the phase-conjugation on bright idler photons, we efficiently perform the wavelength-conversion and since the wavelength of the phase-conjugation photons is the same as that of the signal photons we can performed the target detection based on low-cost classical homodyne balanced detector. To generate entangled photon pairs, we use either C- or L-bands tunable laser, EDFA, the periodically poled $LiNbO_3$ (PPLN) waveguide, and compact coarse wavelength division (CCWDM) demultiplexers. To study the high-potential of the proposed entanglement based radar concept, we have developed an outdoor free-space optical (FSO) testbed at the University of Arizona campus between ECE Department and Meinel buildings. Our recent experimental demonstrations indicate that the proposed entanglement based radar significantly outperforms the corresponding classical counterpart and can operate in beyond strong turbulence regime. The adaptive optics is also used to improve the overall reliability of the radar system.

In the rest of the section, the paper organization is described. The proposed entanglement based radar concept is provided in Section 2. The entanglement based radar FSO testbed is described in Section 3. In Section 4 illustrative experimental results are provided. Section 5 concludes the paper.

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2. ENTANGLEMENT BASED RADAR PERFORIMG PHASE-CONJUGATION ON IDLER PHOTONS

The operational principle of entanglement based monostatic radar technique performing the phase-conjugation on idler photons is provided in Figure 1. The entanglement generation source on transmitter side generates entangled photon pairs: signal photons that are used as the probe signal and idler photons used for local reference, having the same role as the local oscillator laser. The signal photons are pointed towards the target with the help of expanding telescope (beam expander). The signal photons propagate over the atmospheric turbulent channel towards the target. The reflected signal photons, representing the probe signal, are collected by the compressing telescope. At the same time the idler photons undergo the phase-conjugation so that the signal photons and phase-conjugated photons have the same wavelength. The phase-conjugated photons are stored in the quantum memory and interacted with reflected signal photons by the homodyne balanced detector. The quantum phase-correlation between reflected signal photons and idler photons is utilized to improve detection probability of the entanglement-based radar.

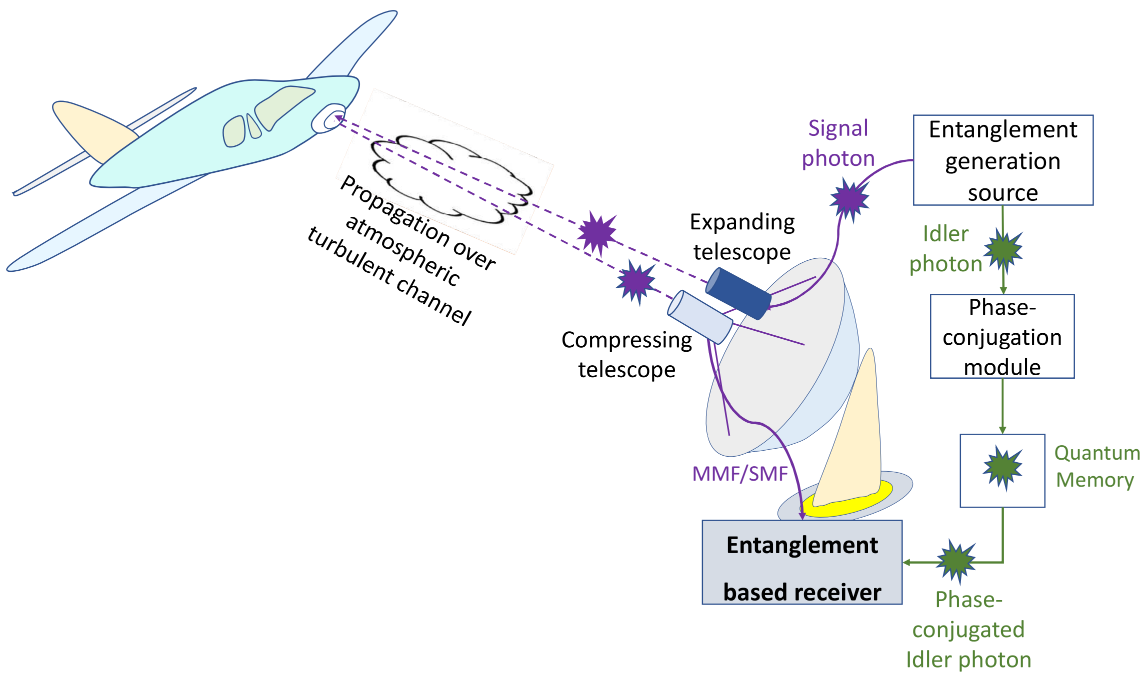
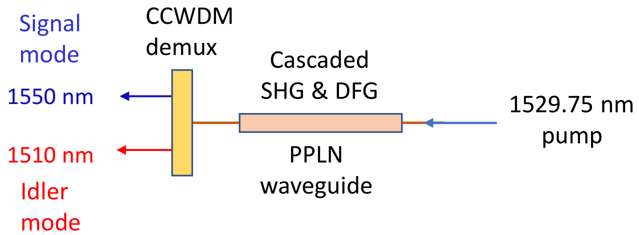


Figure 1. Illustrating the entanglement based monostatic radar concept performing phase-conjugation on idler photons.



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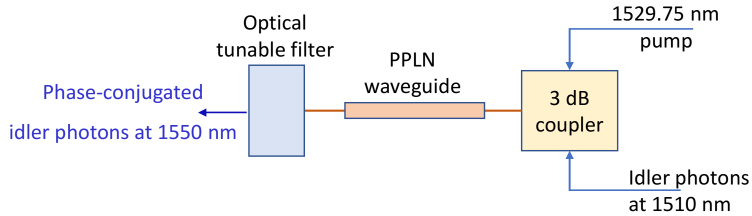


(b)

Figure 2. (a) C/L-band entanglement generation source employing the cascaded SHG and DFG concept and (b) the phase-conjugation of the idler photons by employing combined SHG and DFG concept.

To generate entangled photon pairs traditionally the 780 nm pump lasers have been used. Unfortunately, for high-speed quantum applications, the linewidth should be in order of tens of KHz, and corresponding pump lasers are bulky and extremely expensive. To reduce the system cost, we recently proposed to use the telecom pump lasers instead with the operating wavelength being in either C- or L-band [1],[2]. The proposed entanglement generation source is based on our cascaded second-harmonic generation (SHG) and difference frequency generation (DFG) concept we introduced in [12], and corresponding entanglement generation source is provided in Fig. 2(a). The periodically poled $LiNbO_3$ (PPLN) grating is properly designed such that the SHG dominates in the first half of the PPLN waveguide, which then serves as the secondary pump in the second half of the PPLN waveguide to generate the entangled photons pairs.

To perform the phase-conjugation of idler photons we employ the combined SHG and DFG concept, illustrated in Fig. 2(b). The idler photons at λ_i =1510 nm are combined with the pump signal at λ_p=1529.75 nm. Through SHG the secondary pump signal is obtained. Then through DFG the phase-conjugated idler photons are generated at wavelength $\lambda_{i,PC}=1/(2/\lambda_p-1/\lambda_i)$=1550 nm. Given that reflected signal photons (from the target) and phase-conjugated idler photons have the same wavelength the optical homodyne detection is used to detect the presence of the target.

3. TERRESTRIAL FREE-SPACE OPTICAL TESTBED TO STUDY ENTANGLEMENT BASED RADARS

In order to study the proposed entanglement based radar technique, performing phase-conjugation on idler photons, over turbulent terrestrial FSO channels, at the University of Arizona (UA) campus, we have developed the corresponding test bed, which is shown in Fig. 3. The monostatic quantum radar equipment is located in the Quantum Communication Lab (ECE Room 549), the target, in the form of retroreflector, is placed on the roof-top of the Meinel building that is 750 m away from the ECE Rm 549 window. The tunable pump laser signal is amplified by an the EDFA, whose output is split between the entanglement generation and the phase-conjugation modules. The entanglement generation source is implemented with the help of the PPLN waveguide performing the role of cascaded SHG and DFG module as described in the previous section. The entangled signal-idler photon pairs are separated by the compact coarse WDM (CCWDM) demultiplexer. The signal photons are with the help of the expanding telescope pointed towards the target. The received signal photons, reflected from the target, affected by atmospheric turbulence and other effects, are collected by the periscope and compressing telescope. The portion of the compressed beam (8%) is used to operate the waveform sensor (WFS), the rest is coupled to the multimode fiber (MMF). The signal photons can optionally be phase modulated to improve the radar range as described in [1].

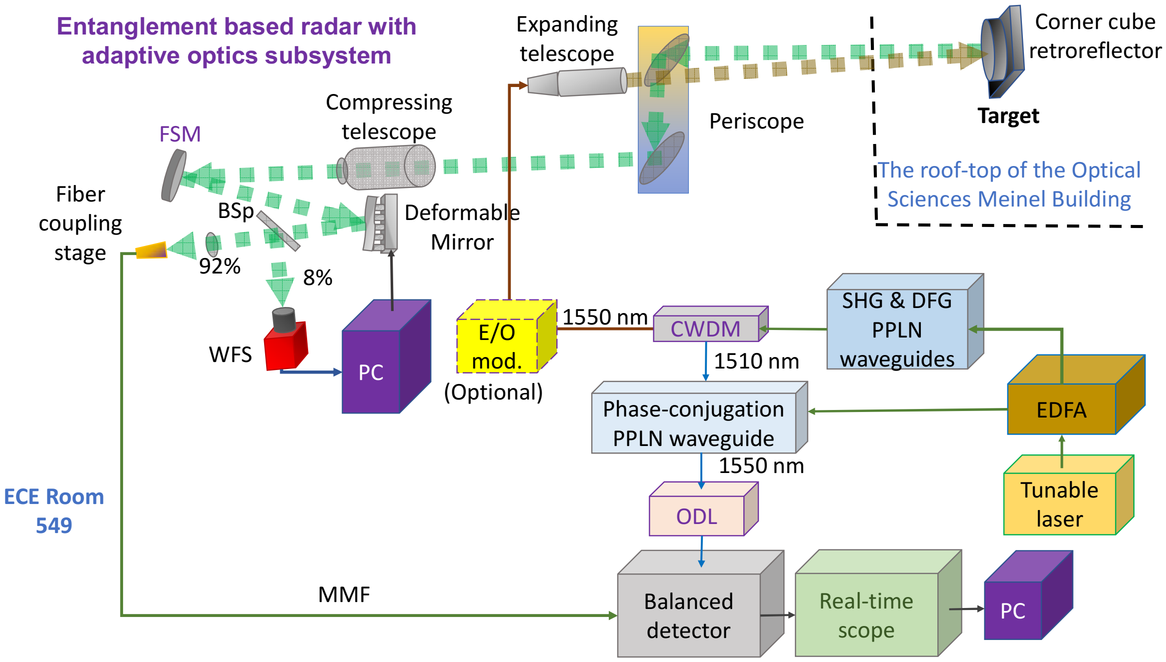


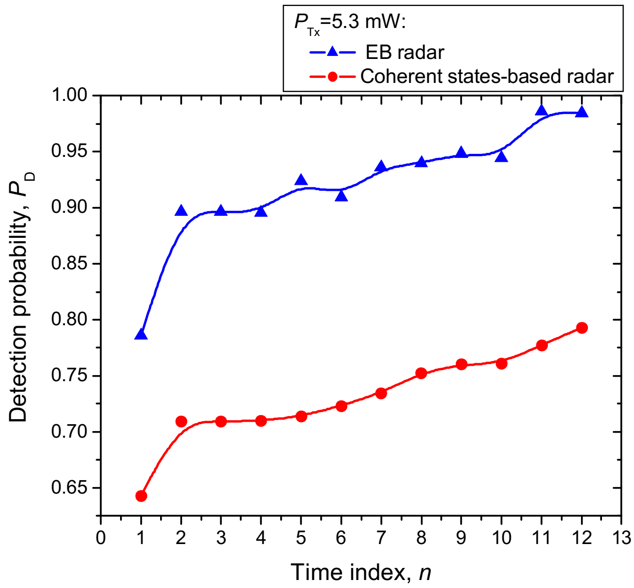
Figure 3. The terrestrial free-space optical entanglement based quantum radar testbed. BSp: beam splitter, WFS: waveform sensor, ODL: optical delay line, E/O mod.: electro-optical modulator (optional), FSM: fast steering mirror.

At the same time, the idler photons are combined with the pump signal before the phase-conjugation module, implemented by using the bottom PPLN waveguide. In the phase-conjugation module the simultaneous SHG and

DFG processes take place, and the phase-conjugated idler photons are selected by the CCWDM demultiplexer. The phase-conjugated idler photons are delayed in the optical delay line (ODL) for the time the reflected signal photons get propagated to the target and back. The delayed phase-conjugated idler photons are mixed with the returned signal photons in the optical hybrid before homodyne balanced detection takes place. The RF signal at the output of the balanced detector is sampled by the real-time scope and transferred to the personal computer (PC), where the target detection takes place.

4. ILLUSTRATIVE EXPERIMENTALL RESULTS

The experimental results conducted on two different days are summarized in Figures 4 and 5. In Figure 4(a) we provide the detection probability results for both entanglement-based (EB) radar and coherent states-based classical radar, for different target detection attempts, obtained on Dec. 11, 2023. In Fig. 4(b) we provide the corresponding histogram of received power. The Rayleigh distribution indicates the strong turbulence regime. Clearly, the EB radar significantly outperforms the classical radar in terms of the detection probability, and is more tolerant to the turbulence effects.



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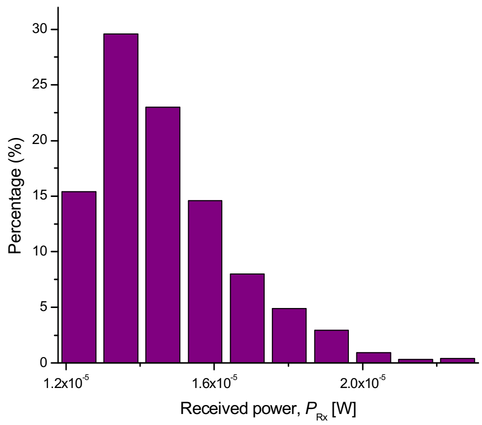
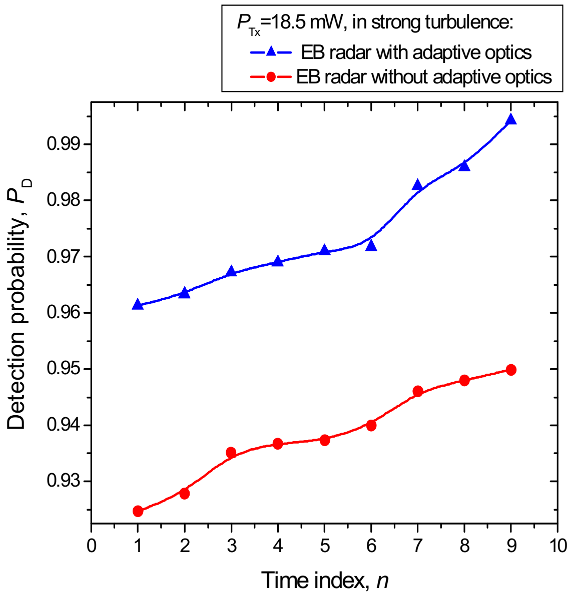


(b)

Figure 4. (a) Entanglement based radar against coherent states-based radar in terms of the detection probabilities P_D for different target detection attempts over FSO channel. The maximum tolerable false alarm probability is fixed to $P_{FA}=10^{-7}$. (b) Histogram of received power. Experiments performed on Dec. 11, 2023.

To improve the detection probabilities the adaptive optics, composed of WFS and deformable mirror, operated in the servo loop, is used, and corresponding results collected on April 18, 2024 are summarized in Fig. 5(a). The corresponding histogram of received power is provided in Fig. 5(b). Again, the Rayleigh distribution indicates strong turbulence effects. Additionally, the Mie scattering effects were strong as well. Evidently, the adaptive optics helps improve the detection probabilities and thus reliability of the EB radar, regardless of the turbulence strength. To ensure that the detection probability is always above 0.9, the higher transmit power of 18.5 mW is used.



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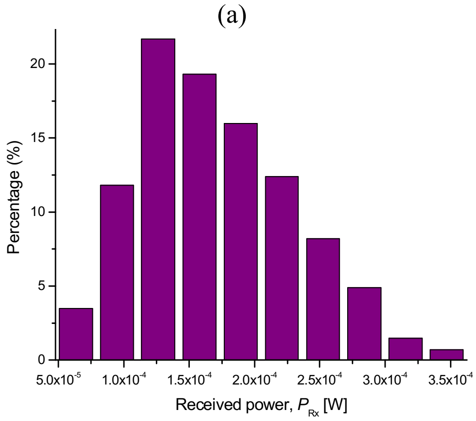

(b)

Figure 5. (a) Entanglement based radar against coherent states-based radar in terms of the detection probabilities P_D for different target detection attempts over FSO channel. The maximum tolerable false alarm probability is fixed to $P_{FA}=10^{-7}$. (b) Histogram of received power. Experiments performed on April 18, 2024.

5. CONCLUDING REMARKS

In this invited paper, we have described our recent research activities on entanglement based radars, operated over the strong atmospheric turbulence channels. In conventional entanglement assisted applications, including quantum radars, optical phase-conjugation, which is required before the homodyne detection takes place, has been on received, weak signal photons. The signal photons propagated over the terrestrial free-space optical links, are affected by various atmospheric effects including diffraction, absorption, scattering, and turbulence. Thanks to these atmospheric effects only a limited number of weak target probe returned signal photons reach the receiver side. Given that is extremely difficult to perform any phase-conjugation on weak signal photons when the average number of received photons is <<1, we have recently proposed to perform the phase-conjugation on the bright idler photons instead [1],[2]. As discussed in [1] there are numerous advantages of performing the phase-conjugation on idler photons. The most important are the following ones. By performing the phase-conjugation on the bright idler photons the efficiency and reliability of the phase-conjugation process is significantly better. In the EB radars, the reflect photons form the target can be coupled to the MMF instead of the single-mode fiber thus further improving the reliability of the system. The receiver sensitivity of the EB based receiver is much better so that we can operate the EB radar in very low signal-to-noise ratio regime.

To reduce the system complexity and cost we use the telecom pump lasers for both entanglement generation and the phase-conjugation modules. To demonstrate the high-potential of the proposed entanglement based radar performing the phase conjugation on bright idler photons, we have developed a terrestrial free-space optical quantum radar testbed at the University of Arizona campus. Using this testbed we have experimentally demonstrated that the proposed entanglement based radar can significantly outperform the corresponding classical counterpart and can even operate in strong turbulence regime and beyond. To improve the detection probabilities further, we have used the adaptive optics.

ACKNOWLEDGEMENTS

This work is supported in part by the NSF (under Grant 2244365) and in part by Dr. Djordjevic discretionary accounts.

REFERENCES

[1] I. B. Djordjevic, V. Nafria, "Entanglement Based Detection, Networking, Sensing, and Radars," *IEEE Photonics Journal*, vol. 16, no. 1, p. 7300610, Feb. 2024.

[2] I. B. Djordjevic, V. Nafria, "Entanglement Assisted Quantum Radar Demonstration over Turbulent Free-Space Optical Channels," in Proc. *Asia Communications and Photonics Conference (ACP) / The International Photonics and OptoElectronics Meetings (POEM) (ACPPOEM) 2023*, November 4-7, 2023, Wuhan, China, doi: 10.1109/ACP/POEM59049.2023.10369590.

[3] V. Nafria, I. B. Djordjevic, "Entanglement Assisted Communication over the Free-Space Optical Link with Azimuthal Phase Correction for Atmospheric Turbulence by Adaptive Optics," *Optics Express*, vol. 31, no. 24, pp. 39906-39916, 8 Nov 2023.

[4] I. B. Djordjevic, *Quantum Communication, Quantum Networks, and Quantum Sensing*. London-San Diego: Elsevier/Academic Press, 2022.

[5] I. B. Djordjevic, "On Entanglement-Assisted Multistatic Radar Techniques," Special Issue Information Theory and Coding for Wireless Communications, *Entropy*, vol. 24, no. 7, p. 990, 17 July 2022.

[6] I. B. Djordjevic, "Entanglement-Assisted Joint Monostatic-Bistatic Radars," Special Issue *Quantum Communication, Quantum Radar, and Quantum Cipher*; *Entropy*, vol. 22, no. 6, p. 756, May 2022.

[7] I. B. Djordjevic, "Entanglement Assisted Radars with Transmitter Side Optical Phase Conjugation and Classical Coherent Detection," *IEEE Access*, vol. 10, pp. 49095-49100, 2022.

[8] I. B. Djordjevic, *Physical-Layer Security and Quantum Key Distribution*. Springer International Publishing AG: Cham, Switzerland; Heidelberg, Germany, 2019.

[9] S.-K. Liao, *et al*., "Satellite-to-ground quantum key distribution," *Nature*, vol. 549, p. 43, 2017.

[10] S. Lloyd, "Enhanced sensitivity of photodetection via quantum illumination," *Science*, vol. 321, pp. 1463–1465, 2008.

[11] M. Lanzagorta, *Quantum Radar*. San Rafael, CA, USA: Morgan and Claypool Publishers, 2012.

[12] T. Liu, I. B. Djordjevic, *et al*., "Broadband wavelength converters with flattop responses based on cascaded second-harmonic generation and difference frequency generation in Bessel-chirped gratings," *Optics Express*, vol. 24, no. 10, pp. 10946-10955, 2016.