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LOW PROBABILITY OF DETECTION AND COVERT RADARS OVER ATMOSPHERIC TURBULENCE CHANNELS BASED ON INCOHERENT LIGHT SOURCES *

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Abstract. *The low probability of detection (LPD) and covert radars concept based on incoherent, broadband thermal optical sources is proposed. The main idea behind our proposal is to hide the radar signal in the background solar radiation by employing the thermal broadband source followed by the EDFA (of 10 dB bandwidth 39.2 nm), modulating the broadband thermal source output beam by a phase-shift keying modulation format at high-speed, and employing the cross-correlation approach in detecting the target. At the University of Arizona campus we developed a terrestrial free-space optical (FSO) testbed to demonstrate the proposed technique. The adaptive optics is utilized to improve the tolerance to atmospheric turbulence effects. The experimental verifications indicate that the proposed LPD/covert radar concept is operational even in beyond strong turbulence regime.*

Key words: *incoherent thermal light sources, radar techniques, free-space optical (FSO) links, low probability of detection radars, atmospheric turbulence channels*

1. INTRODUCTION

The low detection probability radars, also known as the low probability of intercept (LPI) radars, are highly relevant in both defense and commercial applications. The LPI radar is a specially designed radar whose emission spectrum (or waveform) is difficult to intercept and detect by a non-cooperative intercept receiver [2]. The low probability of detection (LPD) radars seem to be an active research area even these days [2]-[4], with recent trends more focused on the various artificial intelligence/machine learning approaches [5],[6].

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The quantum radars can be utilized as an alternative to the LPI radars to improve the target detection probability in a low signal-to-noise ratio (SNR) regime, and to overcome the standard quantum limit [7]-[11]. The complexity and cost of such quantum radar are both too high compared to the classical approaches.

Here we propose the LPI and covert radar techniques by utilizing the incoherent, thermal broadband light sources. The main idea behind our proposed LPI radar concept is to hide the radar signal in background solar radiation while employing the phase-shift keying (PSK) modulation schemes to modulate the broadband source. Given that PSK modulation formats have constant amplitudes it is extremely difficult to detect the presence of such signals. To recover the return radar signal we propose to utilize a simple cross-correlation approach.

At the University of Arizona (UA) campus we developed the terrestrial free-space optical (FSO) testbed, between the building of the Department of Electrical and Computer Engineering (ECE) and Meinel building of the College of Optical Sciences, with the goal to demonstrate the proposed LPI radar concepts. The retroreflector, serving the role of the target, is located on the roof of the Meinel building. The roof of the Meinel building is 750 m away from the window of ECE building, Rm 549, where optical transceiver is located. Our experimental findings indicate that broadband, thermal incoherent light sources can be utilized to operate the LPI/ covert radars in beyond strong turbulence conditions. To improve the detection probabilities in the presence of atmospheric turbulence effects the adaptive optics (AO) is utilized.

In the rest of this section, organization of the paper is provided. Section 2 is devoted to the proposed LPD/covert radar concepts. The terrestrial, outdoor FSO LPI/covert radar testbed is described in details in Section 3. In Section 4, the experimental findings are summarized. The Section 5 is devoted to the conclusion.

2. Proposed Incoherent Source-based LPD Radar Technique

The LPI/covert radar concept, introduced in this paper, is provided in Fig. 1.

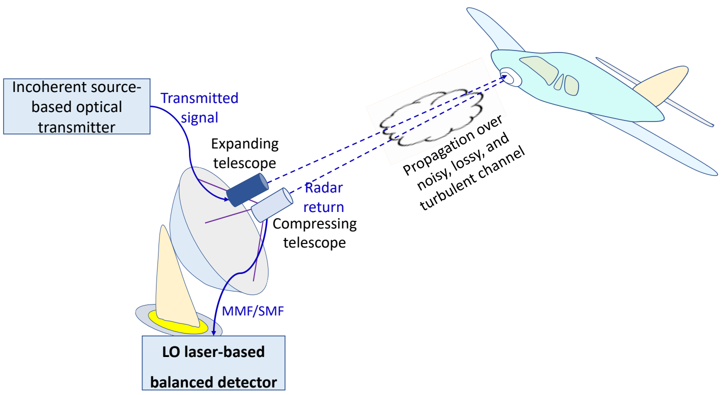

Fig. 1 The proposed LPI/covert radar technique employing incoherent thermal sources

To implement the proposed LPI/covert radar we propose to hide the radar signal in solar background radiation. By ensuring that the radar signal has the same distribution as the solar background radiation it is extremely difficult to distinguish the radar signal from the background solar radiation. Further, the M-ary PSK is utilized to modulate the known sequence to the receiver. Given that the amplitude of M-ary PSK is constant, it is extremely challenging to intercept by *Willie*. In covert/LPI communications and sensing *Willie* is significantly more powerful than Eve, because he not only can eavesdrop the channel but also shut it down. The incoherent, thermal source beam is first phase modulated, then amplified, and finally transmitted over lossy, atmospheric turbulent channel, affected by the background solar radiation, towards the target. The radar return beam signal is collected by the receiving telescope and detected by the balanced heterodyne detector. In balanced detector we mix the received broadband, thermal signal with the LO laser at 1550 nm, used to detect the position of the known sequence. Because the distribution of the transmitted signal is the same as the solar background radiation, and at the same time the transmitted signals is hidden in the solar background radiation, it will be extremely difficult for *Willie* to either intercept or detect such radar signal.

3. Description of Experimental Testbed

In order to study the proposed LPI/covert radar concepts over turbulent terrestrial FSO channels, we developed the FSO testbed shown in Fig. 2. The proposed LPI/covert radar concept employs the incoherent, thermal source and in addition to radars it can also be used in sensing, LIDAR, and communication applications. Most of the equipment is located in the ECE Room 549, hosting the Quantum Communications (QuComms) Lab. The corner-cube retroreflector, serving the role of the target, is located on the rooftop of the Meinel building. The retroreflector/target is 750 m away from the window of the QuComms Lab (in ECE Rm 549). The terrestrial FSO testbed, developed to study the proposed LPI/covert concepts, is divided into several stages: (i) incoherent, thermal source and phase-modulation stage; (ii) optical transceiver subsystem; (iii) FSO link with the corner-cube retroreflector (serving as the *target*); (iv) adaptive optics (AO) subsystem; and (v) heterodyne balanced detection detector.

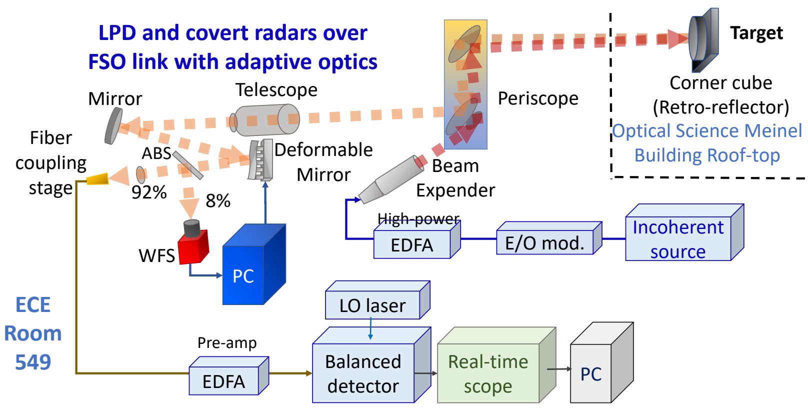

Fig. 2 FSO LPI/covert radar experimental testbed with adaptive optics, employing incoherent, thermal source. PC: personal computer, ABS: asymmetric beam splitter, WFS: wavefront sensor, EDFA: Erbium-Doped Fiber Amplifier

In our experiment, we utilize the broadband thermal source whose output is amplified by the C+L-band Erbium-Doped Fiber Amplifier (EDFA), and the output of EDFA has the 10 dB bandwidth of 39.2 nm, and is used as an incoherent, thermal source. The corresponding spectrum at the output of EDFA is given in Fig. 3. We used a binary PSK (BPSK) signal to transmit the sequence that is already known to the receiver. This known sequence is used as a unique signature BPSK sequence. The transmitted data is organized in packets, with content known to the receiver in advance. To determine the position of the known sequence and thus identify the presence of the target, the receiver employes the cross-correlation method. To compensate for the insertion loss of the phase modulator and adjust the launch power, we utilize a high-power EDFA. The output of the high-power EDFA is set to 100 mW. The output of the high-power EDFA is launched into free space by a beam expender and a periscope. (Because the window of the QuComms Lab is small and not in the same level as the corresponding optical table we applied the periscope approach to solve for this problem.) The periscope is composed of three mirrors as shown in Fig. 2. The two inch mirror and common mirror are used as transmit side periscope, while the common mirror and receive mirror as the receive side periscope. The transmit side periscope beam output is pointed toward the Meinel building and it is reflected back by the retroreflector placed on the Meinel building rooftop, which serves as the target. At ECE Room 549, this returning radar beam is first collected by the receive side periscope and then propagated over the adaptive optics subsystem on an optical table (see Fig. 4 for details). After the AO subsystem, the reflected beam was coupled into an optical fiber by the fiber coupling stage. The radar return signal coupled into fiber is further amplified by a low-noise, high-gain amplifier. Finally, the received radar return signal is mixed with the local oscillator (LO) laser signal at 1550 nm by using the OptiLab balanced detector (of 23 GHz bandwidth). The LO signal wavelength is properly selected to match one of the FSO telecommunication windows with low scattering effects [12]-[14]. Because the non-coherent source has a large bandwidth of 39.2 nm, all signal photons within the bandwidth of the balanced detector (23 GHz) around the LO signal at 1550 nm will be detected. Therefore, here we perform both homodyne and intradyne detection simultaneously. The RF output of the balanced detector is then transferred to the Tektronix real-time oscilloscope to sample the received return radar signal waveform

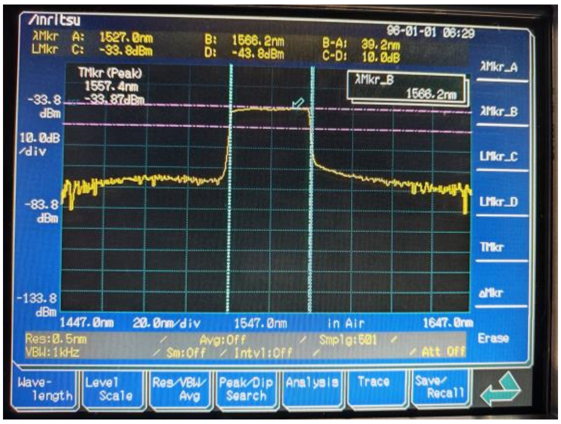

Fig. 3 Wavelength spectrum of the EDFA source

and further analyze it for the presence of the target. Further, the cross-correlation method is employed to detect the presence of the return radar signal. The transmitted sequence is known at the receiver side, so the receiver shifts the sampled sequence sample by sample until maximum of cross correlation is found. If the cross correlation maximum is larger than the optimum threshold, the presence of the reflected signal is declared. The threshold is optimized to maximize the detection probability.

The AO subsystem was used to improve the tolerance to the atmospheric turbulence effects. It contains the wavefront sensor (WFS) (from Active Optics Systems, LLC) and a deformable mirror (DM) (from Boston Micromachines Corporation) and they are operated in a feedback loop. The WFS is used to estimate the wavefront distortions introduced by the turbulence. The personal computer (PC) is further used to determine the corresponding correction signals to be applied to the DM. The corresponding actuators deform the mirror trying to compensate for the wavefront distortions and undo the action of the FSO channel. To reduce the system complexity and corresponding cost, the 8% of the radar return signal is used as a beacon signal to operate the AO stage. We use the BPSK unique sequence as the probe signal because the BPSK transmission is robust in turbulent channels and has constant amplitude so that portion of received power can be used to operate the AO subsystem.

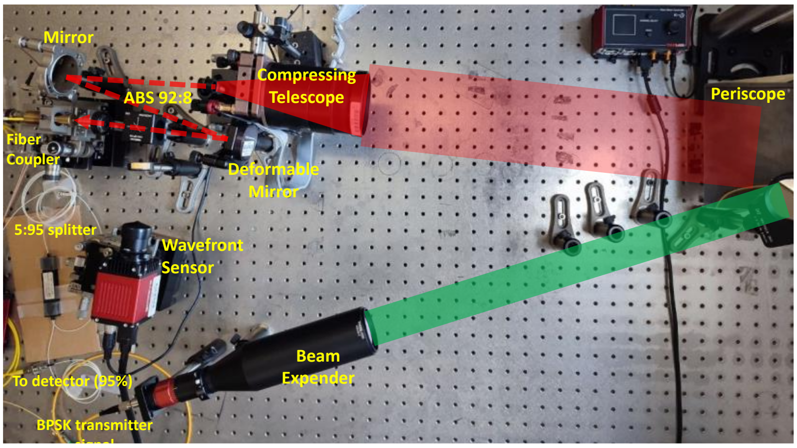

Fig. 4 Details of the optical transceiver and adaptive optics

4. ILLUSTRATIVE EXPERIMENTAL FINDINGS

The LPD/covert radar experiments were performed on April 20, 2023, in a strong turbulence regime for different turbulence realizations, and corresponding target detection probabilities are summarized in Figure 5. The corresponding received power histogram, provided in Fig. 6, follows a Rayleigh distribution and based on refs. [12], [13] we conclude that the turbulence conditions were strong. Other weather conditions were: temperature 25^{o}C, humidity 7%, wind 2.9 m/s West, and atmospheric pressure 699 mmHg. We compared detection probabilities using the BPSK at 10 Gb/s and 20 Gb/s, with and without AO, by utilizing the incoherent, thermal source. The incoherent, thermal source transmit signal bandwidth was 39.2 nm, launch signal power was 100 mW, and measured background solar radiation (in the 76-mm diameter aperture) of the receive side telescope (also known as the compressing telescope) was 41.36 mW. Even though that the AO is designed to operate in a weak turbulence regime, it still provided relevant improvements in the target detection probabilities in strong turbulence regime, for the proposed incoherent, thermal light source based LPD radar technique. From Figure 5 we conclude that lower signaling rate (10 Gb/s) case provided better detection probabilities compared to the higher signaling rate (20 Gb/s) case.

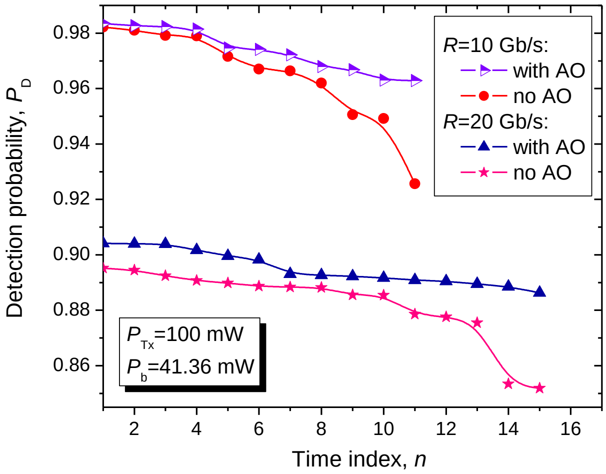

Fig. 5 The target detection probabilities for the proposed LPI radars for different atmospheric turbulence realizations. The probe signal is composed of the unique BPSK signature sequence. Time indices denote different transmissions of the unique sequence. Transmission experiments were conducted on April 20, 2023; and the false alarm probability was 10^{-6}

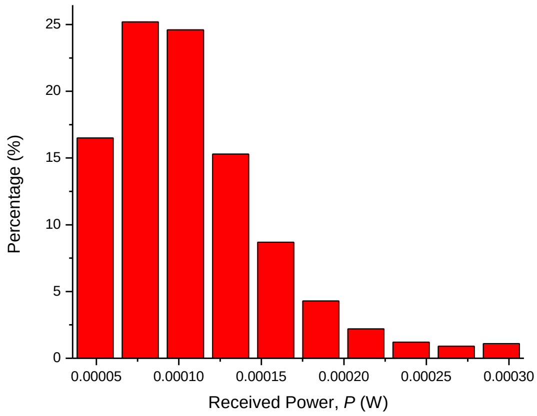

Fig. 6 Received power histogram collected on April 20, 2023

In addition to experiments summarized in Fig. 5, we also performed experiments on April 26, 2023, and in Fig. 7 we provide the target detection probabilities for 10 Gb/s and 5 Gb/s signaling rates. The turbulence conditions were strong. Other weather conditions were: temperature 28ºC, humidity 11%, wind 3.2 m/s NW, and atmospheric pressure 696 mmHg. The launch power was 100 mW, while the measured solar background radiation in the 76-mm diameter aperture of the receive telescope was 37.08 mW. In this experiment, the adaptive optics feature was turned off. Clearly, as expected, the 5 Gb/s signaling rate case exhibited much better tolerance to the strong turbulence effects compared to the 10 Gb/s signaling rate case.

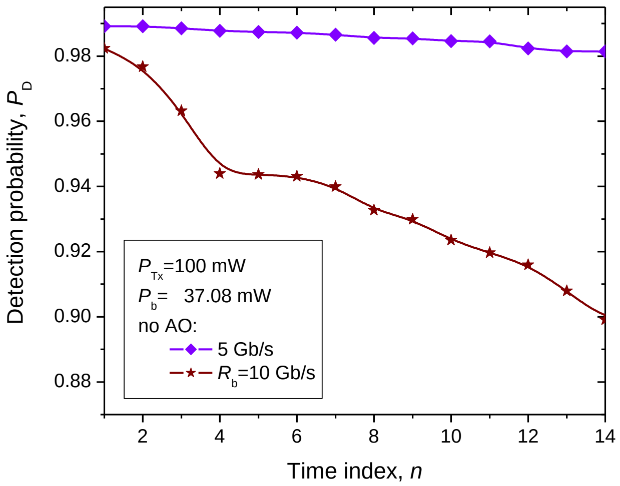

Fig. 7 Target detection probabilities for the proposed LPI radars for different atmospheric turbulence realizations. Transmission experiments were conducted on April 26, 2023 and the false alarm probability was 10^{-6}

5. CONCLUSION

We have proposed the low probability of intercept and covert radar concepts by utilizing the broadband thermal, incoherent light sources. The key motivation for this proposal has been to hide the radar signal in solar background radiation. To do so we have used the broadband thermal light source, which output signal has exactly the same distribution as the solar background radiation. To avoid affecting the amplitude of the thermal source we have proposed to use the phase-shift keying modulation formats, such as BPSK, which represent the modulation schemes with constant amplitude, to impose the known signature sequence. Simple cross-correlation method has been used to detect the LPI/covert radar return.

At the University of Arizona campus, we have established the terrestrial FSO link between ECE and Meinel buildings, which is of length 750 m, to perform experimental verifications. The performed experiments were conducted in a desert environment in the strong turbulence. In Section 4, we have specified other relevant weather conditions. Experimental findings indicate that the broadband thermal, incoherent light sources can be utilized to operate the LPI and covert radars under strong atmospheric turbulence conditions (in a desert). Adaptive optics has been used to improve the detection probabilities. Even though the AO has been designed for astronomy, which systems are typically operated in the weak atmospheric turbulence, we have demonstrated that the AO can improve the tolerance to turbulence effects even in the strong atmospheric turbulence. The proposed AO subsystem does not require the utilization of the reference (beacon) for proper operation. The 8% of constant amplitude modulated radar return signal has been utilized in AO subsystem to operate seamlessly.

The proposed LPI and radar concepts have been evaluated in a C-band centered at 1550 nm. Other relevant transmission wavelength windows to be evaluated in the future include 2.2 µm, 3.5–4.1 µm, and 10 µm.

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