Improved Target-Detection Signal-to-Noise Ratio
via Quantum Illumination

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Abstract: We report the first experimental demonstration of quantum illumination's signal-to-noise ratio advantage over classical (laser-light) illumination for target detection in a lossy, noisy scenario.

Entangled light beams are a fundamental quantum-mechanical resource, with applications to Heisenberg-limited precision measurements [1], teleportation [2], and quantum cryptography [3]. However, loss and noise quickly destroy optical entanglement, limiting many of its uses to low-noise environments. Quantum illumination [4] is different: it is predicted to offer a significant performance improvement—in comparison with classical (laser-light) illumination of the same average power—precisely when the propagation environment is lossy and noisy, i.e., entanglement breaking.

Consider the idealized optical radar that uses a T-s duration single spatial-mode optical pulse of average photon number N_T to interrogate a spatial region that is equally likely to contain or not contain a weakly-reflecting target embedded in a high-brightness thermal background. Regardless of target absence or presence, this background returns an average photon number $N_B \gg 1$ per temporal mode to a single spatial-mode radar receiver. If this is a classical illumination (CI) radar, then optimal quantum processing of the single spatial-mode light returned from the region of interest will declare the target's absence or presence with an error probability satisfying $\Pr(e)_{\text{CI}} \sim \exp(-\kappa N_T/4N_B)/2$, where $\kappa \ll 1$ is the roundtrip transmissivity of the transmitter-to-target-to-receiver path when the target is present [4]. In a quantum illumination (QI) radar, the transmitter employs a single spatial-mode, continuous-wave spontaneous parametric downconverter (SPDC) to produce entangled signal and idler beams, transmitting a T-s burst of signal with average photon number N_T to interrogate the target region, while retaining (without loss) the companion idler light for subsequent joint measurement with the return from that region. If the joint measurement realizes the optimum quantum processing for deciding between target absence or presence, the resulting error probability will satisfy $\Pr(e)_{\text{QI}} \sim \exp(-\kappa N_T/N_B)/2$, when the SPDC operates in its usual low-brightness regime, wherein N_S, its average signal (and idler) photon number per mode, obeys $N_S = N_T/TW \ll 1$, with W being the SPDC's phase-matching bandwidth [4]. The exponents in $\Pr(e)_{\text{CI}}$ and $\Pr(e)_{\text{QI}}$ are $1/8$ of their receiver's respective signal-to-noise ratios (SNRs), so that QI with optimum quantum reception is seen to enjoy a 6 dB SNR advantage over CI with optimum quantum reception. This advantage occurs even though $N_B = \kappa$ suffices for entanglement breaking, i.e., $N_B \geq \kappa$ makes the joint state of the QI receiver's retained and returned light classical when the target is present.

Optical homodyne detection provides an excellent approximation to optimum quantum reception for a CI radar, but no explicit realization is known for QI's optimum quantum receiver. Quantum illumination derives its performance advantage from the stronger-than-classical phase-sensitive cross correlation between the SPDC's signal and idler beams. A low-gain optical parametric amplifier (OPA) can convert the residual phase-sensitive cross correlation—when the target is present—between the return from the target region and the retained idler into interference that can be measured, to advantage, in a direct-detection receiver [5]. With lossless idler retention, such an OPA receiver yields a QI error probability satisfying $\Pr(e)_{\text{OPA}} \sim \exp(-\kappa N_T/2N_B)/2$, when $N_S \ll 1$ and $N_B \gg 1$, i.e., a 3 dB SNR advantage over the CI radar. We report the first experimental demonstration of quantum illumination's SNR advantage over classical illumination for such a lossy, noisy scenario by comparing the SNRs of CI-homodyne and QI-OPA receivers for a weakly-reflecting target in the presence of a bright background source.

Fig. 1(a) shows a schematic of the experimental quantum illumination setup. The source for our QI setup is a type-0 SPDC that uses a periodically-poled lithium niobate (PPLN) crystal pumped at 780 nm to create non-degenerate signal and idler beams at 1638 and 1500 nm respectively that are separated from the pump and each other by a series of dichroic mirrors. A variable attenuator imposes controlled signal loss, after which the attenuated signal is sent through a square-wave phase modulator whose half-period takes the role of the theory's pulse duration. Noise from

a 1638 nm broadband diode laser is combined with the phase-modulated signal on a 50-50 beam splitter. A prism mounted on a translation stage adjusts the signal path length. The signal, idler, and pump beams are recombined with dichroic mirrors and focused into a second PPLN crystal that forms the low-gain OPA. The OPA's idler-port output is isolated with dichroic mirrors and detected by an InGaAs avalanche photodiode in conjunction with a low-noise transimpedance amplifier. The absence (presence) of a target is simulated by blocking (opening) the signal path.

Our CI source is a 1558 nm narrowband diode laser, whose output is split with 90% used for the homodyne-detection local oscillator (LO) and 10% as the target-probing signal. A variable attenuator is used to match the target-present classical signal power at its homodyne receiver's input to the corresponding target-present QI signal power at its OPA receiver's input. The classical signal is then sent through a square-wave phase modulator and combined—on a 50-50 beam splitter—with amplified spontaneous emission (ASE) noise from an erbium-doped fiber amplifier (EDFA). This ASE has been filtered to 1558 ± 0.35 nm so that its average photon number per mode at the input to the CI receiver's homodyne detector matches the corresponding per-mode noise entering the QI receiver's OPA. The return signal (containing the added noise) is combined with the local oscillator on a 50-50 beam splitter and balanced homodyne detection is performed.

The Fig. 1(b) points are QI SNR measurements versus the small-signal gain $(G-1)$ of the OPA for three values of the average background photon number per mode, N_B, with $\kappa = 0.05$. The measured QI SNRs match the expected dependence on N_B when the detector noise is included (dashed lines) and signal brightness N_S is used as a fitting parameter. The thick solid lines are the expected QI SNR when the InGaAs APD's noise (excess noise factor $F \approx 6$) is removed, increasing the SNR by ~ 1.5 dB. In comparison, the thin solid lines are the measured CI SNRs for the same background noise levels as in the QI measurements, showing that out QI receiver would achieve higher-than-classical SNR if its detector noise could be overcome. (Note that the CI receiver uses PIN diodes with the same quantum-efficiency ($\eta = 0.83$) as the QI APD and has sufficient LO power to approach shot-noise limited operation).
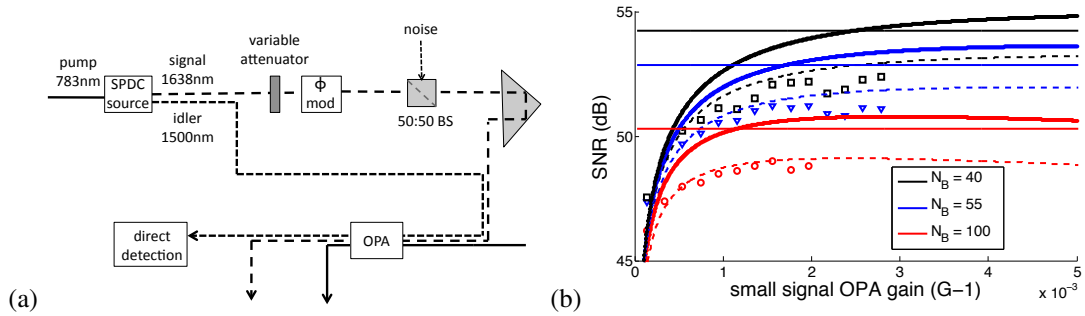

(a) (b)

Fig. 1. (a) Schematic of the QI experiment. (b) QI SNR versus CI SNR: both transmitters have average photon number N_T, both propagation paths have $\kappa = 0.05$ transmissivity, and both receivers suffer the same background noise N_B. The idler has a storage transmisstivity $\mu = 0.8$. Measured QI SNRs (data points) are in good agreement with theoretical values (dashed lines) that include detector noise. The measured CI SNRs (thin solid lines) exceed the measured QI SNRs, but when the QI detector-noise is removed the QI SNRs (thick solid lines) exceed the CI SNRs by ~ 0.5 dB. QI parameters: $N_S = 0.0025$ and $TW = 1.45 \times 10^{12}$.

A comparison between the measured CI SNR and the measured QI SNR—adjusted to account for APD excess noise in the QI receiver—shows that QI provides a ~ 0.5 dB advantage over CI for the given parameters, a clear experimental demonstration that the entanglement-based QI setup offers a target-detection performance gain over a CI system of the same transmitted power, despite the entanglement-breaking nature of the environment.

References

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