Correction of atmospheric turbulent effects with a double fast steering mirror system for free-space quantum communications

**MOTIVATION**

Free-space quantum communication systems require beam stabilization techniques to compensate for the effects of atmospheric turbulence, such as beam wander, which provokes random fluctuations of the beam centroids at the receiver, inducing optical losses of the quantum signal. These fluctuations are due to wavefront distortions or aberrations of the first order (δρ and δθ) which can be corrected with fast actuators and position sensitive detectors. In moderate to high turbulent regimes (Cn² of 10⁻⁴) correction on the receiver is sufficient to compensate turbulent effects in propagation distances of typically less than 1 km before achieving pre-compensation of the emitter is also necessary. The simplest configuration consists of a fast steering mirror in a PIDs loop to minimize the error caused by deviations measured on a position sensitive detector. However, this setup can only correct for deviations in the beam in a single spatial plane. A double-mirror correcting system stabilizes the beam in the whole optical axis making its implementation ideal for a quantum receiver.

**ATMOSPHERIC TURBULENCE EFFECTS**

Refractive index fluctuations due to movements of air masses from thermal gradients cause different effects on a beam, such as beam spreading and beam wander. The first is caused by small eddies compared to the beam diameter and originates an enlargement of the beam beyond that caused by refraction divergence. Larger eddies cause deflections of the beam, changing the angle of arrival at the receiver, which translates into a random dancing of the beam in the receiver plane.

**CORRECTING WITH FSMS AND PSD**

**FAST STEERING MIRROR (FSM)**
- Push pull coils
- Maximum angular deviation (Δθ)
- Resolution = 2 µrad
- Internal PSD to monitor position
- Measured bandwidth = 500 Hz

**QUADRANT Position Sensitive Detector (QD-PDS)**
- Segmentor or quadrant detector
- Blind area or gap
- Better resolution and accuracy than lateral effect detector
- Resolution NOH dependent on SNR
- Response dependent on light spot profile

**Lateral-Effect Position Sensitive Detector (LE-PDS) DETECTOR**
- Non-segmented lateral-effect detector
- Wider dynamic range (Ns PE)
- Independent on light spot profile
- Resolution dependent on SNR

**DOUBLE-MIRROR CORRECTING SYSTEM**

- Fixing an optical beam spatially in two points allows stabilization along a whole optical axis (corrected beam in diagram).
- The correcting system in Bob has two Fast Steering Mirrors (FSMs) connected to two position sensitive detectors (quadrants).
- Each mirror fixes the beam in one spatial point.
- FSM₀ is PID looped with QD₀ and FSM₁ with QD₁.

**CALIBRATION OF THE SYSTEM**

Setting up the positions of QD₀ and QD₁
- Position of QD₀, image plane of FSM₀
- Position of QD₁, the closest to the focus of the lens

This allows to increase the distance between the two fixed points to the maximum

\[ \text{Correcting factor } c = \frac{c_1}{c_2} \]

Relative correcting factor: \( c = 0.7 \)

Setting up the values of PID₀ and PID₁
- Rising times slow to reject high frequency turbulent effects due to oscillations.
- FSM₀ faster than FSM₁ to enable a more efficient correction.

**EXPERIMENTAL RESULTS**

**Probability density function of the correction**

**Correlation along the optical axis of the receiver**

**Stability of the correction**

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