2004 Quantum Optics Group

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Papers and Projects in 2004

- 12 Refereed articles in 2003
- 10 Refereed articles in 2004
- Tripartite quantum state sharing
- Squeezing in the audio gravitational-wave detection band
- Quantum cryptography without switching
Our presentation

• Ping Koy:
  – Audio frequency squeezing experiment.

• Ping Koy:
  – Quantum cryptography theory

• Thomas:
  – Quantum cryptography experiment.
  Could we have another *Phys. Rev. Lett.* Please?
Audio Freq. Sqz for Grav. Wave Detection

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Gravitational Waves

Black Hole Binary & Ripples in Space-Time
Techniques for reducing optical noise

- Nonlinear / quantum technique
- Common mode rejection technique
- Active feedback control technique
- Passive environmental stabilization technique

- Resonant relaxation oscillation noise
- Laser phase noise
- Photo-refractive noise (phase matching)
- Photo-expansive noise (heating)
- Pump noise (green light)
- Seed noise (IR light)
- Quantum noise
- Acousto-optic noise
- Electro-optic noise
- Electrical noise (power supplies)
- Cross talk (lack of balancing, polarization extinction)
- Beam pointing noise
- Detector noise
- Resonator noise (detuning)
- Compound cavity/ Intra-cavity noise
Previous Low Frequency Results

- Recent CW LF Results include
  - 220kHz - W.P. Bowen et al. [1]
  - 80kHz - R. Schnabel et al. [2]
  - 50kHz - J. Laurat et al. [3]

All experiments rely mostly on common mode noise cancellation!

OPA/OPO Theory II

The variances in the frequency domain for the OPA/OPO output are:

\[ V_{\text{OUT}}^\pm(\omega) = C_s V_s^\pm(\omega) + C_l V_l^\pm(\omega) + C_v^\pm(\omega) V_v^\pm(\omega) + \alpha^2 \left( C_p V_p^\pm(\omega) + C_A^\pm V_A^- (\omega) \right) \]

\[ \uparrow \quad \uparrow \quad \uparrow \quad \uparrow \quad \uparrow \]

Seed \quad Loss \quad Vacuum \quad Pump \quad Detuning

(f < 2MHz) \quad (f < 2MHz) \quad (f < 50kHz)

For below threshold OPO \( \alpha = 0 \) and \( V_s^\pm = I \):

\[ V_{\text{OPO}}^\pm(\omega) = C_s + C_l + C_v^\pm(\omega) \]

**OPO is immune to laser noise, pump noise and detuning noise!**

No one really have experimentally done an OPO squeezing experiment properly!
OPA Squeezed Quadrature Spectrum

Locked Squeezed Quadrature Spectrum

RBW = 128Hz, RMS averages = 1000, Electronic noise (at -12dB) subtracted from all traces
OPO Squeezing Without/With Isolator

RBW = 8Hz, No.RMS ave = 400 without isolator, 500 for QNL and with Isolator. Electronic noise (not shown) was not subtracted.
OPO Squeezed Quadrature Spectrum

Locked Squeezed Quadrature Spectrum

From 100Hz-3.2kHz: RBW = 8Hz, no. RMS ave = 500
From 1.6kHz-12.8kHz: RBW = 32Hz, no. RMS ave = 1000
From 3.8kHz-100kHz: RBW = 128Hz, no. RMS ave = 2000

Conclusions & Future Work

Conclusions

• Need to get rid of almost all IR photon to get real OPO!
• 200Hz Squeezing.
• Noise locking technique to lock a squeezed vacuum.

Future Work

• To get down to 10Hz in squeezing
  – Photo-thermal analysis, line-noise subtraction, more advanced locking loops.
• To get 10 dB squeezing
  – New GrIIRA free crystals
  – Increase OPO escape efficiency
  – Increase observable universal by a factor of ~36.
The BB84 Protocol

What do we need to implement quantum cryptography?
What role does quantum mechanics play?

[Bennett and Brassard, Proceedings IEEE., (1984)]
Necessary ingredients for QKD

- Single photons...
- Qubits...
- Squeezing...
- Quantum correlations (sub-quantum noise correlations)...
- Entanglement...
- Alice and Bob share more information than Eve ($I_{AB} > I_{AE}$)...
- Bob needs to randomly switch measurement basis...

None of the above!
Really necessary ingredients for QKD

- We only need 2 things

- Differential correlations
  - Alice and Bob shares different information from Alice and Eve

- Known bounds
  - Heisenberg uncertainty, no-cloning limit, Shannon, entropy, etc.
  - There exist classical information protocols to distill secret key, amplify privacy, reconcile data remotely.

A great number of QKD proposals are overkills!
Continuous Variable Quantum Cryptography

- No need single photon, squeezing, entanglement... Just coherent states
- No need to switch measurement basis
Quantum Cryptography without Switching

The Simultaneous Quadrature Measurement (SQM) Protocol.

- Alice: Encodes random numbers on both non-commuting quadratures on a coherent state.
- Alice: Transmits the coherent states.
- Bob: Measures both quadratures simultaneously.
- Analyse SQM protocol in the context of Grosshans and Grangier reverse reconciliation protocol.
G&G Reverse Reconciliation (GGRR)

- **Direct reconciliation**
  - Bob tries to guess what Alice has sent.
  - Loss 50% => Eve has the upper hand.

- **Reverse reconciliation**
  - Alice tries to guess what Bob has measured.
  - Loss of any amount still has Alice knowing more than Eve.
Secret Key Rate

\[ \hat{X}^\pm_{E|B} = \hat{X}^\pm_B - \alpha \hat{X}^\pm_E \]
\[ \hat{X}^\pm_{A|B} = \hat{X}^\pm_B - \beta \hat{X}^\pm_A \]

\[ I = \frac{1}{2} \log_2 (1 + S/N) \]

\[ [\hat{X}^+_E|B, \hat{X}^-_{A|B}] = [\hat{X}^+_B, \hat{X}^-_B] = 2i \]

\[ \Delta I = \Delta I^+ + \Delta I^- \]
\[ = (I^+_{BA} - I^+_{BE}) + (I^-_{BA} - I^-_{BE}) \]

\[ \Delta I = \frac{1}{2} \log_2 \left( \frac{V^+_E|B V^-_E|B}{V^+_A|B V^-_A|B} \right) \]
The SQM Protocol - Results

$$\Delta I = I_{BA} - I_{BE}$$

$$\Delta I \geq \log_2 \left( \frac{\frac{\eta}{V_A} + (1 - \eta)V_N}{\eta + (1 - \eta)V_N + 1} \right)$$

No Switching

Switching
The SQM Protocol - Results

• Experimentally a lot simpler
  – The process of switching in continuous variables, limits the bandwidth in the cryptographic protocols.

• Applicable to all existing CVQC.
Virtual entanglement

Real entanglement

No entanglement

Virtual entanglement