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Interferometric Measurement with Squeezed Light

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Introduction

The main goal of our research is the achievement of substantial squeezing of the vacuum fluctuations associated with a soliton. If the soliton is injected into the probe port of a Mach-Zehnder interferometer and the squeezed vacuum is injected into the vacuum port, sub-shot noise measurements of the phase difference between the two arms of the interferometer can be performed. The soliton squeezing is being done in a Sagnac loop. This objective calls for:

a. The development of pulse sources of 1GHz or higher rep-rate to combat Guided Acoustic Wave Brillouin Scattering

b. Development of an amplifier that brings the pulses to the energy level required for subpicosecond soliton propagation in the fiber loop

c. An understanding of the noise of the pump

d. Demonstration of squeezing

All four of these objectives have been accomplished as shown in detail in the report. The first three accomplishments have the potential to affect source development for optical communications. The squeezing obtained is the best yet demonstrated by anyone. We expect further improvements with proper refinements of the system.

A GHZ Regeneratively Synchronized Passively Modelocked Fiber Laser

Wavelength division multiplexing (WDM) multiplexes different wavelength channels on the same fiber to increase the capacity of the lightwave transmission system. As the number of channels increases in such a system, the number of transmitters increases as well if one transmitter is used for each channel. Thus a broadband pulsed laser that can provide many channels from a single source maybe a viable alternative.[4] In addition to being broadband, the laser source should have gigahertz (GHz) repetition rate(rep-rate) since the transmission speed is determined by the laser repetition rate, and be synchronizable to the system clock. Active modelocking incorporates a modulator in the laser cavity to provide GHz rep-rate and clock synchronization. However it only produces picosecond pulses even in the presence of pulse shortening mechanisms such as soliton effects.[5] Passive modelocking can provide broad bandwidth but the ones that do have low rep-rate.

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13. ABSTRACT *(Maximum 200 words)*

The main goal of our research is the achievement of substantial squeezing of the vacuum fluctuations associated with a soliton. If the soliton is injected into the probe port of a Mach-Zehnder interferometer and the squeezed vacuum is injected into the vacuum port, sub-shot noise measurements of the phase difference between the two arms of the interferometer can be performed. The soliton squeezing is being done in a Sagnac loop. This objective calls for:

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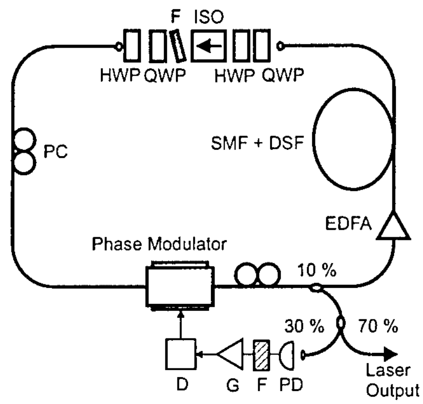

Figure 1. Laser Schematic, HWP: Half Wave Plate; QWP: Quarter Wave Plate; PC: Polarization Controller.

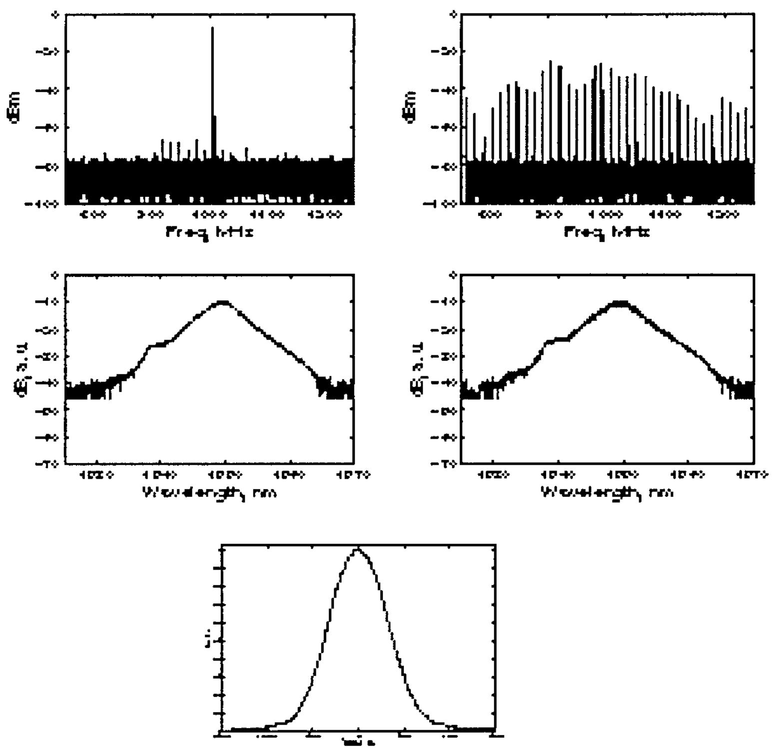

Figure 2. Output of the laser: a) RF spectrum b) optical spectrum when the modulator is on, c) RF spectrum d) optical spectrum when the modulator is off; e) Autocorrelation of the laser output when the modulator is on. The pulsewidth is 480 fs.

We add a modulator in a passively modelocked laser to achieve broad spectrum at GHz rep-rate and clock synchronization. The laser schematic is shown in Fig. 1. Part of the optical output is detected electronically and amplified to drive the phase modulator. The RF and the optical spectra of the output when the modulator is on are shown in Figs. 2a and 2b. The RF suppression is >60 dB and the spectral FWHM is 5.6 nm. Figures 2c and 2d show the RF and the optical spectra when the modulator is off. The absence of regenerative feedback leaves the pulses in random time slots (Fig 2c) but the envelope of the spectrum remains essentially unchanged (Fig. 2d). Thus passive modelocking shapes the pulses. The excellent RF suppression in Fig. 2a shows that the modulator synchronizes the pulses and prevents pulse dropouts. The pulsewidth is 480 fs and is shorter than what is possible via harmonic modelocking with solitonic shortening.[6] The amplitude and timing jitter of the laser are measured to be 0.03% and 86 fs, respectively. Figure 3 the shows the seventh harmonic of the laser. The jitter is low-frequency and mainly due to white noise. The inset shows the jitter's quadratic dependence on harmonics. We have developed a noise theory and the jitter can be accounted for when ASE is assumed to be the sole noise source.

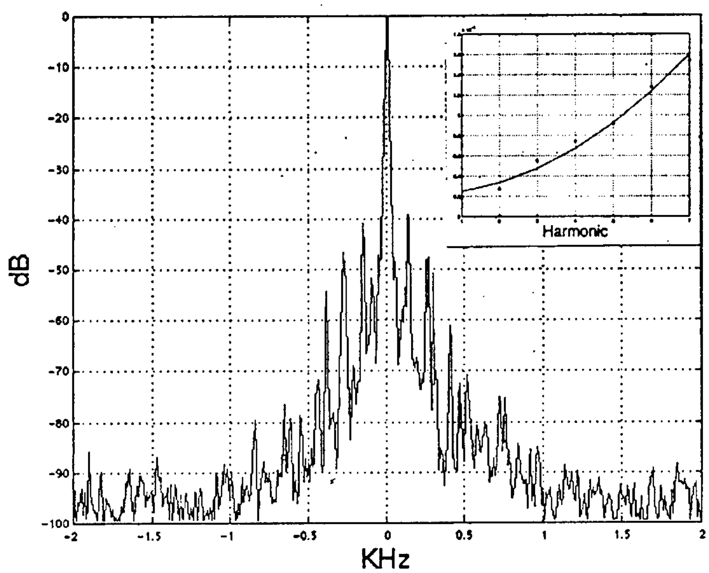

Figure 3
Harmonic seven (inset: quadratic jitter fitting).

Quantum Noise of Mode-locked Lasers

Passively mode-locked fiber lasers have an unusually small pulse-timing jitter.[1,2] The pulse-stream can provide accurate time delays for sampling applications. There is particular interest in the application to broadband A to D converters which need accurate sampling.

This is the motivation for the determination of the ultimate lower limit on the timing jitter set by quantum noise. We have developed a fully quantum mechanical analysis of the noise in passively mode-locked solid state lasers. Each gain or loss element within the laser is a source of quantum noise (zero point fluctuations). A filter with frequency dependent loss also contributes noise. This noise is fundamental and unavoidable and sets a lower limit on the noise of the system. If the system emits soliton-like pulses, the pulses have four degrees of freedom: amplitude, phase, position and momentum. All of these are noise driven and fluctuate. Their fluctuations have been evaluated. It is of interest to note that the fluctuations inside the laser are different from those that would be derived from a semi-classical theory (signal plus additive noise power). On the other hand, the fluctuations of the emitted pulses outside the laser derived from quantum theory check with the predictions of the semi-classical theory.

If the pulse-stream is to be timed, active mode-locking is necessary. We have developed the quantum theory of actively mode-locked lasers.[3] With an eye on semiconductor lasers, we have allowed for gain relaxation times comparable to the pulse width. Under these conditions, amplitude fluctuations translate into timing jitter. As a consequence, the timing jitter of semiconductor lasers is inherently larger than that of solid state or fiber lasers.

Soliton Squeezing in Optical Fiber

Highly accurate optical phase measurement apparatuses such as the laser gyroscope are increasingly being deployed in many applications that require inertial navigation and platform stabilization. Many of these sensors use an interferometric arrangement to sense any motion. The accuracy of such high precision phase sensitive interferometric measurements is fast approaching the limits set by the shot noise, which originates from fluctuations of the vacuum field. It has been shown[7] that an interferometric phase measurement can achieve higher SNR than the standard quantum limit by using "squeezed" states. Squeezed quantum states of the electromagnetic field are states that have reduced fluctuations in one phase of the field at the expense of increased fluctuations in the quadrature phase. We have pursued the generation of squeezed states in fibers since their use in a measurement has to be accomplished with minimum loss. Single mode fibers and their interconnections can be made with very small insertion losses. We have been able to observe 5dB squeezing using pulses at 1.3 mm[9]. The squeezing is limited because different temporal portions of the Gaussian pulse do not interact with each other. Each portion experiences different nonlinearity depending on its amplitude and thus different amount of squeezing. The overall squeezing is an average over the entire pulse. Because of the low peak power in the pulse wings the overall squeezing cannot improve.

To overcome this limitation we will attempt squeezing at 1.55 μm. At 1.55 μm the fiber has negative dispersion and the pulses form solitons. The different temporal portions of an ideal soliton are correlated with each other and experience the same squeezing. Thus no limit due to the pulse shape exists for soliton squeezing. Theoretical analysis indicates that greater than 20 dB squeezing is achievable before the Raman effect places a floor on the observable squeezing.

Past efforts to observe soliton squeezing have largely been frustrated by Guided Acoustic Wave Brillion Scattering(GAWBS)[7]. GAWBS is a phase noise generated in fiber due to the fiber's acoustic modes and cannot be cancelled via balanced detection. GAWBS usually has frequency content from 20 MHz to 1 GHz. To combat GAWBS we use a pulsed source whose repetition rate is greater than 1 GHz. Squeezing can then be observed between GAWBS spikes. We have achieved a 1 GHz fiber laser source using harmonic modelocking[8]. To reach the soliton condition we need ~150 mW in one single polarization. Such power is difficult to achieve directly from the laser or even from a conventional fiber amplifier. We have made a double-clad Er/Yb fiber amplifier with gain fiber donated by Lucent Technologies. Greater than 1 Watt of saturated power has been obtained with this amplifier. We are optimizing this amplifier to achieve 2 Watts of saturation power stably. Amplification with the current amplifier configuration leads to pulse peak power in excess of 1 kW, more than sufficient for our squeezing experiments.

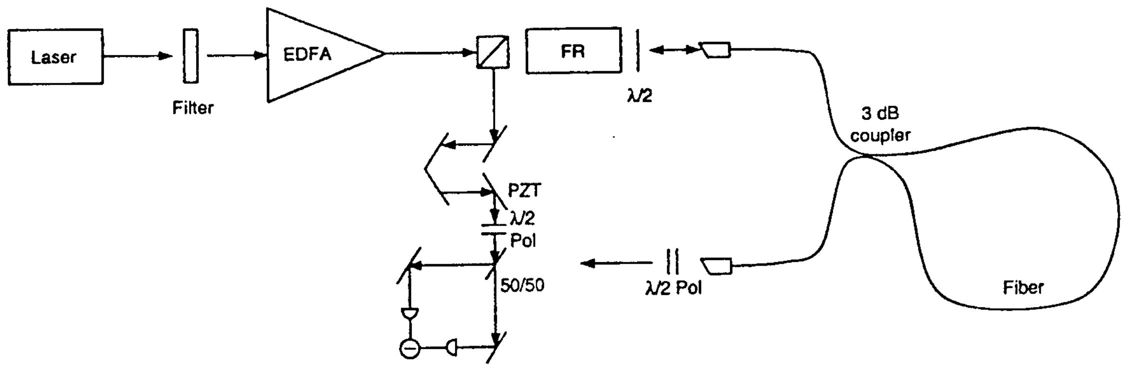

Figure 4. Schematic setup.

The amplified output is sent into a balanced Sagnac loop mirror[9]. The schematic is shown in Fig. 4. The input is reflected back towards the amplifier but the circulator separates it so that it can be reused as the local oscillator (LO) for homodyne detection. The squeezed vacuum exits the vacuum port and meets the LO at the 50/50 beam splitter. The two beams are carefully matched in space, time and polarization. A balanced detector is used to cancel the classical noise of the LO. The noise of the amplified pulses is 18 dB above the shot noise for 5-10 MHz. Our balanced detector can cancel 27 dB of noise. We have also calibrated our detector with flashlights and verified the shot-noise levels. Thus our detector output is shot-noise limited for that frequency. Figure 5 shows the averaged normalized power spectrum at 10 MHz with and without the squeezed vacuum when the PZT is driven slowly with a sawtooth and 3 dB of squeezing has been observed. Because our interferometric setup is not stabilized, the phase between the LO and the squeezed vacuum slips and the averaged results show less squeezing than the actual amount. Though too noisy to be conclusive, single-shot spectra seem to suggest at least 5 dB squeezing. We are currently building a feedback stabilization circuit to observe this large squeezing.

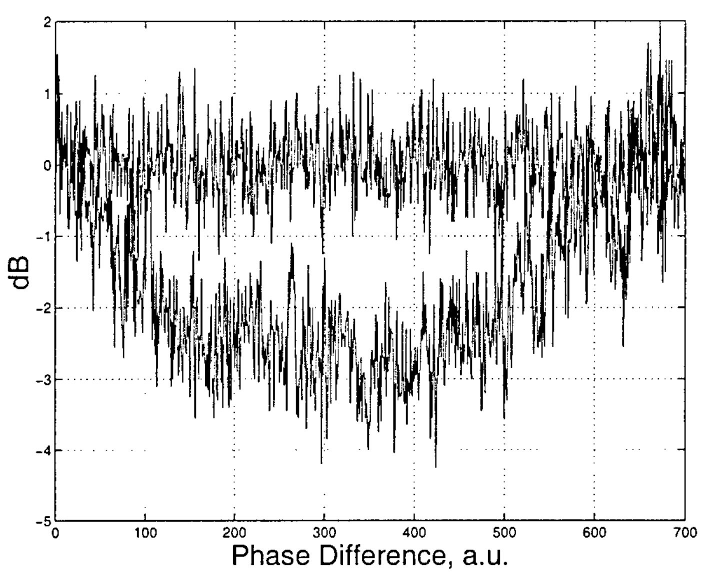

Figure 5. Squeezed spectrum and shot noise spectrum

Configuration Space Methods in Quantum Optics

We are pursuing a configuration space approach to quantum optics problems, which describes an optical system in terms of the coordinates of the photons. We have recently found a new physical interpretation of the Gordon-Haus effect which arises from this point of view [Fini, et. al., Phys. Rev. A 60:2442,1999]. While the second-quantized approach attributes the noise to vacuum fluctuations injected during loss and gain processes, the configuration space calculation shows that the noise is a direct result of the discreteness of loss and gain interactions. These are of course complementary descriptions: they are dual aspects of the quantum nature of the field. Our recent calculation thus supports the old result, and shows that each approach can uncover intuition that the other misses.

The mechanism by which discreteness of energy exchange causes noise is surprisingly simple. When a photon is lost from the soliton, it can have any frequency within the classical soliton spectrum. Each lost photon that is redder than average causes an effective blue shift (and conversely) simply because it carries with it less (more) than the average energy. We have shown that when this basic effect is rigorously calculated, it agrees exactly with the second-quantized calculation.

We have taken this model further by generalizing the quantum nonlinear Schrödinger equation to two polarization states [Fini, et. al., paper accepted by QELS'00]. The mapping of second-quantized to configuration space models is performed, and the bound states are given in a Hartree approximation. Within this framework, we can sensibly generalize the Gordon-Haus effect to PMD-induced losses. This is an interesting example where the usual result is enhanced due to shaping of the loss spectrum.

Publications acknowledging ONR

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