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13. ABSTRACT (Maximum 200 words)

The theoretical and experimental work in this reporting period was concerned with the generation and utilization of squeezed pulsed radiation. Improved sensitivity of fiber gyros with noise levels below the shot noise level is one possible utilization of such radiation.

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Annual Report
"Interferometric Measurement with Squeezed Light"
Grant No.: N00014-92-J-1302
January 1, 1997 - December 31, 1997

P.I.'s: H. A. Haus and E. P. Ippen
Staff: Dr. Shu Namiki, visiting scientist
Dr. Moti Margalit, post-doc
Patrick Chou, graduate student
Charles X. Yu, graduate student

Goal of Research

The theoretical and experimental work in this reporting period was concerned with the generation and utilization of squeezed pulsed radiation. Improved sensitivity of fiber gyros with noise levels below the shot noise level is one possible utilization of such radiation.

Soliton Squeezing

Guided Acoustic Wave Brillouin Scattering (GAWBS) reduces the squeezing achievable via nonlinear propagation in fibers. The effect of GAWBS can be reduced either through the use of pulse trains of higher than 1GHz repetition rate so as to avoid the appearance of noise sidebands generated by GAWBS in the measurement window, or through the use of intense pulses passing through short fibers. In the latter case, use is made of the differences in the evolution of squeezing on one hand, and of GAWBS on the other hand. The pulse-rate can be low. Thus, this experiment can employ pulses generated by our stretched pulse fiber ring lasers that emit pulses at low rates (100MHz).

(a) Cross-Phase Modulation Squeezing

Experiments have begun on the squeezing of solitons of high intensity in short fiber segments. We used cross-phase modulation. The vacuum in one polarization is squeezed by the "pump" pulse in the other polarization, co-traveling with the vacuum. The vacuum is separated out at the output with a polarization sensitive beam splitter. Shot noise reduction of 3 dB was achieved. The details have appeared in the new Internet journal^[1].

(b) Soliton Squeezing in Sagnac Loop

We used harmonically modelocked 1 Gbit/s pulse trains with 500 fs pulses for injection of solitons into a Sagnac loop. The high bit-rate was used to suppress the noise due to Guided Acoustic Wave Brillouin Scattering (GAWBS). These pulses were not amplified. At the pump energy of 20 pJ used and a pulse width of 500 fs, the predicted Kerr phase shift in the Sagnac loop of 200 m length was 1.5π . Whereas noise below the shot noise level was observed, the level of noise suppression was not stable. We attribute this behavior to

uncontrolled variations in the phase difference between the squeezed vacuum and the pump reused as the local oscillator. Experiments with a shorter loop of 50 m, on the other hand, did not give significant amounts of squeezing. Here, however, it appeared that the pump energy was insufficient to produce suppression of noise below the shot noise level of the balanced detector current. We have investigated the following mechanisms that affect the degree of squeezing:

1. The frequency dependence of the coupling ratio of the fiber coupler in the Sagnac loop. If the carrier frequency of the pump pulses is adjusted to coincide with the frequency of 50/50 coupling, then pump leakage into the vacuum port would have to produce a spectrum with two peaks with a zero at the carrier frequency. Such behavior was not observed, leading us to conclude that this effect is not a serious one.
2. Use of a secant hyperbolic local oscillator signal. Theory shows that the secant hyperbolic local oscillator pulse is sub-optimal for the detection of the squeezed vacuum. Yet, it is the pulse-shape delivered directly from the squeezer. Any attempts at pulse reshaping incur unavoidable phase shifts that are difficult to control. Hence, any practical realization of a squeezing apparatus is compelled to the use of such pulse shapes. Further analysis reveals that the penalty for the use of a secant hyperbolic pulse is not severe. Yet, it is one of several effects that diminish the amount of squeezing for small squeezing angles^[2].

Direct Measurement of Self-Phase Shift

In the unsuccessful squeezing experiments in the Sagnac loop the question arose as to the Kerr phase shift produced by the available powers propagating in the loop. Hence we asked the question whether the self-phase shift phase shift could be measured directly. The experiments reported below demonstrated the feasibility.

We have devised a novel method to measure this phase shift based on Spectral Interferometry (SI)^[3]. SI measures the sum spectrum of a reference and a signal that are coherent and separated in time by τ . The beating between signal and reference generates a sinusoid in frequency whose period is the inverse of the temporal separation τ . We ensure that only the signal, not the reference, is affected by the fiber nonlinearity. So the nonlinear phase imposed on the signal distorts the signal-reference beating sinusoid. Near the center of the spectrum the distortion is manifested by a shift of the beating pattern, and the shift is a direct measure of the phase at the peak wavelength. We have shown numerically that it approximates well the nonlinear phase shift at the temporal peak of the pulse.

We have implemented this technique in an experiment using 1.7 km of fiber. We tuned our optical source so that the fiber dispersion was negative or positive depending on the wave-length of the optical signal. We observed that for the positive dispersion case the spectrum broadens as the input power increases. The nonlinear phase shift also increases linearly with input power. For the negative dispersion case the spectrum narrows as the input power increases because of soliton effects. The nonlinear phase shift also increases initially. However, when the soliton condition is reached, both the spectral bandwidth and

the nonlinear phase shift stay the same. This is because an increase of the input power beyond the soliton limit generates continuum and does not contribute to the soliton energy. These experimental observations agree well with our theoretical calculations and numerical simulations. Figure 1 shows some of the experimental results. Figure 1a shows the optical spectrum of the pulse pair before and after the fiber for negative dispersion. Figure 1b shows the same spectra on an expanded 1nm scale. The fringes are uniform and the phase shift can be easily deduced.

The results were published^[4].

Modelocked Laser Sources for Gyro Applications

If squeezed radiation, generated by pulsed excitation in a fiber is to be used in a fiber gyro, the gyro must be pulse excited. We have studied pulse excitation of a Draper fiber gyro. Not unexpectedly, the high intensity of the pulses introduces deleterious nonlinear effects. If the pulses are dispersed before entering the gyro by being transmitted through a dispersive fiber, these effects can be avoided and the performance of the gyro approaches that of a gyro excited by incoherent radiation of the same bandwidth.

The excitation of the gyro with coherent broadband radiation opens up new possibilities for source development for gyro and sensor applications. The spectrum of a coherent source can be feedback controlled more easily than that of an incoherent source. Stabilization of the center frequency of the spectrum may be a desirable feature, not as easily implemented with an incoherent source. The work on pulse excited gyros is continuing. The student working on the project, Patrick Chou, is now fully funded by Draper Laboratory.

Quantum Theory of Soliton Propagation

The theory of generation of squeezed solitons calls for a self-consistent quantum theory of soliton propagation. We have been using the theory developed by Lai and Haus^[5] and Haus and Lai^[6]. The second quantized field on the fiber was derived from a Bethe ansatz, or from the linearized form of the Nonlinear Schrödinger equation. Since the equations are derived from a Hamiltonian, they conserve commutator brackets and are free of distributed noise sources. The theory by Carter and Drummond^[7] was aimed at computer implementation and derived for the c-number generalized Glauber representation $P(\alpha, \beta)$. Their theory contains distributed noise sources. It appears, therefore, that there is a basic disagreement between the two theories. A detailed analysis revealed that the two theories lead to the same expectation values. The noise sources introduced by Carter and Drummond are needed to represent the statistical character of the evolution of the input conditions, whereas the second-quantized approach incorporates the evolution via the quantum uncertainty "ab initio". This work has been accepted by *Phys. Rev. A*^[8].

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Papers and Talks acknowledging ONR support

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Awards received by Prof. Haus in 1997:

1. 1997 Ludwig Wittgenstein Preis Award of the "Österreichischer Forschungsverband, Austria

Awards received by Prof. Ippen in 1997:

1. 1997 Arthur Schawlow Award of the American Physical Society
2. 1997 Quantum Electronics Award of the Laser and Opto-Electronics Society

Figure Captions

- 1a. Spectra before and after fiber, 20 nm span
- 1b. Spectra before and after fiber, 1 nm span for different powers, negative dispersion loop mirrors.

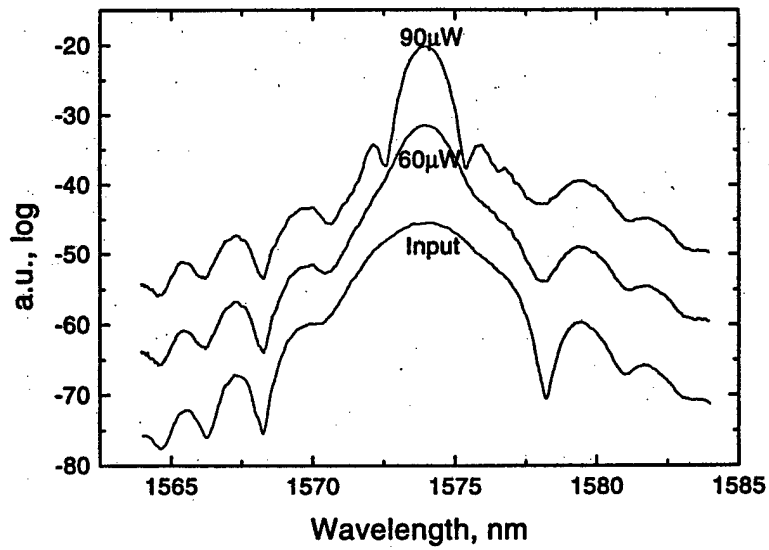


Figure 1a. Spectra before and after fiber, 20 nm span.

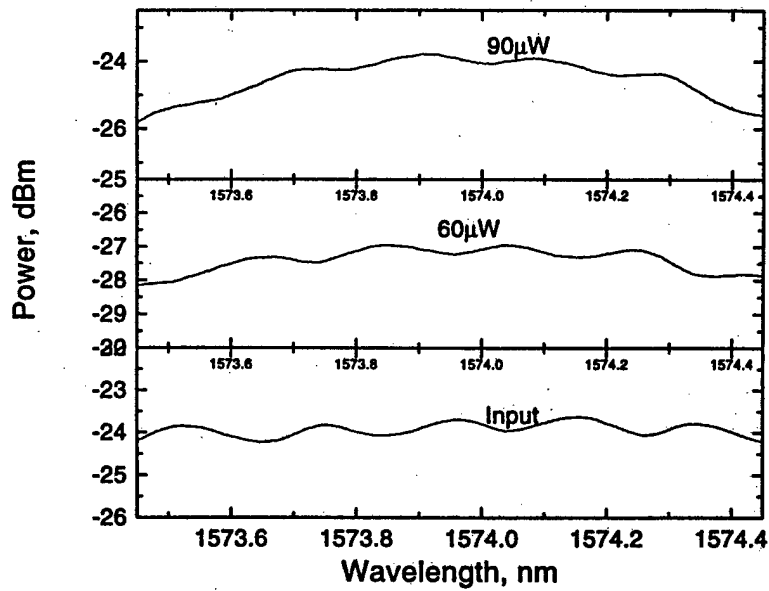


Figure 1b. Spectra before and after fiber, 1 nm span for different powers, negative dispersion loop mirrors.

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