Soliton squeezing generated in an all-fiber configuration

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We experimentally demonstrate amplitude squeezed soliton utilizing intensity-dependent self-phase modulation in an asymmetric Sagnac interferometer. The system, whose components are connected via ferrule connector/physical connection (FC/PC) fiber connectors, constitutes all-fiber configuration to generate squeezed soliton. Soliton amplitude reduction measured by homodyne detection is near 4.0 dB below the shot-noise level. Optimal squeezing fields in both simple and compact all-fiber configuration are obtained.

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Squeezing state refers to that the quantum fluctuations in one of the quadudratures of the fields are below the usual limit for a coherent state. As essential resources, it has shown wide applications in quantum information, e.g., teleportation, continuous variable cryptography, and quantum computing[1,2]. Since the first squeezing field was achieved in degenerate four-wave in a Na atomic beam, it has been analyzed extensively both in theories and experiments[3−6]. There are continuous wave (CW) or pulsed squeezing, which, in general, can be obtained through nonlinear interaction, such as parametric down-conversion, second-harmonic generation, four-wave mixing, self-phase modulation, and cross-phase modulation[7−10]. Compared with CW squeezing, pulsed squeezing has more advantages, especially in achieving stronger squeezing. So it has been shown more potential in the development of generating nonclassical field. Various experiments have been completed to obtain pulsed squeezing. The balanced Sagnac interferometer was implemented in the original pulsed squeezing experiment. Then there have been Mach-Zehnder interferometer and asymmetry Sagnac interferometer. Meanwhile, different wavelengths have been adopted in pulsed squeezing experiments in which some are centered at zero-dispersion of optical fiber or suitable for forming soliton. Soliton has stable characteristic in the temporal and spectral domain due to the balance of group velocity and self-phase modulation when it transmits in optical fiber. Theoretically, soliton amplitude squeezing can be more than 10 dB, which is almost the maximal squeezing value in the prediction of all schemes.

In this letter, we report experiment on the amplitude-squeezed soliton by intensity-dependent self-phase modulation in an asymmetric Sagnac interferometer. In contrast to the setup reported by Schmitt *et al.*[11], we use a 2×2 fiber coupler as beam splitter. Thus all the components including pump source, beam splitter, and high nonlinear coefficient single mode fiber are connected via ferrule connector/physical connection (FC/PC) fiber connectors, which constitutes all-fiber configuration to generate amplitude squeezed soliton. The system is stable, feasible, and compact, which is promising in the network of quantum communication in the future.

The experimental setup is depicted in Fig. 1. Our laser source produces 120-fs (FWHM) sech-shaped optical pulses at a center wavelength of 1550 nm with a repetition rate of 50 MHz. The output power can be adjusted. The asymmetry Sagnac interferometer used for generating directly detectable amplitude squeezed solitons consists of 2×2 fiber coupler and high nonlinear coefficient single mode fiber (Nufren, mode field diameter (MFD) = 6.6 ± 0.2 μm). The wideband 2×2 fiber coupler has 90:10 splitting ratio, in which one port connected to the light source, two ports connected to a fiber of 8-m length forming a Sagnac loop, and the last port as output one. The input power of Sagnac interferometer is split into strong and weak pulses respectively which propagate in opposite directions through the fiber loop. After a round trip they interfere and leave the interferometer. The strong pulse can evolve squeezing due to intensity-dependent self-phase modulation, whereas the weak one is taken as affiliated actor used to adjust the orientation of the soliton squeezing in order to obtain directly detectable measurement. The single mode fiber has a dispersion of $\beta_2 \approx -18.6$ ps^2/km and nonlinear coefficient $\gamma = 3.1$ W^{-1}·km^{-1}, and the peak power and average power required to produce a fundamental soliton are around 1290 W and 10 mW, respectively.

The quantum amplitude fluctuations associated with the pulses are analyzed with a homodyne detection system. It consists of a 50:50 beam splitter and two matched detectors. The bandwidth of the detector needs to be large enough to detect the light effectively, but at the same time, large bandwidth may lead to saturation of the

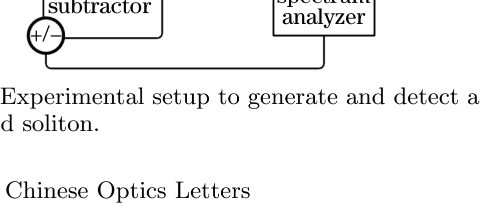

Fig. 1. Experimental setup to generate and detect amplitude squeezed soliton.

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photo diode and transimpedance amplifiers. After trading off between bandwidth and saturation power of the detector, the 3-dB bandwidth of each detector is adjusted to 10 MHz in this balanced detection system. The adder and subtractor consisting of ZSC-2-2-1 and ZSCJ-2-2 (Mini-Circuits Ltd. Co.) is followed by a HP8591E power spectrum analyzer. The sum of the current represents the photo-number or amplitude fluctuations of the detected light and the different current is used for shot-noise calibrations.

The key part of the detector is ETX-500 InGaAs PIN photo diode due to its high quantum efficiency (90% at wavelength of 1.55 μm) and excellent noise performance, which converts the light signal into electric signal. The amplifying circuit for electric signal has two stages. The first stage using CLC420 op-amp converts the current signal into voltage signal, which is powered by the ±5 V voltage and has a maximal output of about 4 V. The second stage using CLC430 op-amp is powered by the ±15 V voltage, which has a maximal output of about 12 V. We adjusted the feedback resistance to match the dynamic range of the two stages.

Our initial experimental investigation about input-output power transfer characteristic of the asymmetric Sagnac interferometer was done by varying the input pulse power continuously, then measuring output power accordingly. The results of the measurements are shown in Fig. 2(a). The trace showed nonlinear distinctly, while exhibiting flat in some regions. It is the consequence of photon-number or amplitude soliton squeezing occurring. The magnitude of amplitude squeezing is determined by comparing the intensity fluctuations of the squeezing with that of the standard quantum limit of pulse which has the same energy. The pulse noise fluctuation, compared with shot-noise reference level which is set to zero on a logarithmic scale, is shown in Fig. 2(b). We set the spectrum analyzer to zero-span state in a narrow-band interval and centered at 5 MHz frequency with a resolution of 10 kHz. For every input power of Sagnac interferometer, one data point of noise is calculated by root mean square (RMS) through 401 data points recorded by spectrum analyzer. The range of input power of Sagnac interferometer is $22-29$ mW which is scaled taking connector losses into account. The largest squeezing occurs when input energy is 27.2 mW, which accords to an approximate order of 1.6 soliton units. The noise reduction below shot-noise level is near 4 dB, which is measured by homodyne detection.

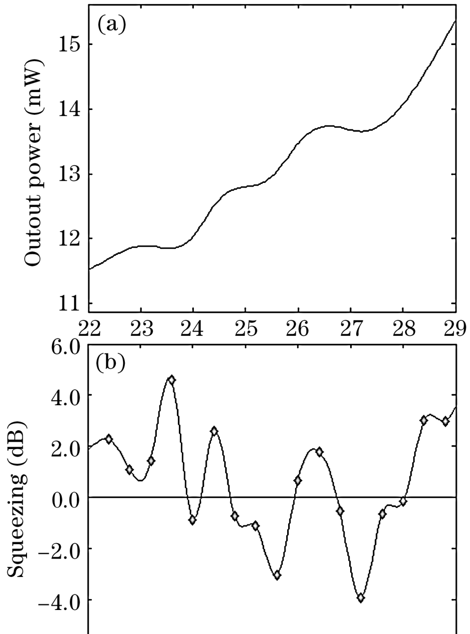

Fig. 2. Measurement results. (a) Input-output power transfer curve; (b) pulse noise fluctuation compared with shot-noise.

We have implemented successful experiment in obtaining soliton amplitude squeezing. Particularly, the system is all-fiber configuration, with each component connected via FC/PC connectors. It is high effective, compact, and practical and would be used in the future quantum communication.

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