A Broadband All-Fiber SU(1,1) Interferometer

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Abstract: We describe an SU(1,1) interferometer based on highly nonlinear optical fiber, attaining >97% peak interference visibility and >90% visibility over a 554 GHz optical band.

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Conventional interferometer interactions correspond to the SU(2) group, and when injected with squeezed light promise to achieve Heisenberg-limited interferometric phase sensitivity [1]. An alternative approach to reach this limit is the SU(1,1) interferometer, sometimes called a nonlinear interferometer because it replaces the linear beamsplitters in conventional interferometers with parametric amplifiers for mode mixing [2]. The first SU(1,1) interferometer was reported in 2011 [3]. With the addition of a coherent seed as one of the inputs, the phase sensitivity of such an SU(1,1) interferometer scales better than a standard linear one, by a factor proportional to the parametric amplifier gain, while offering improved tolerance to loss compared to squeezed-state-injected linear interferometers [4]. Since then, interest in this approach has steadily grown, with a number of experimental SU(1,1) interferometer demonstrations primarily using the $\chi^{(3)}$ nonlinearity in Rb-85 vapor cells [3, 5–10] and also, very recently, using $\chi^{(2)}$ nonlinear crystals [11]. Here we report experimental realization of an SU(1,1) interferometer using highly nonlinear fiber (HNLF), offering high gain, broad bandwidth, and passive stability, making it well suited for all-fiber distributed sensors.

The experimental setup is shown in Fig. 1. A mode-locked pump laser (33.3 MHz repetition rate, ∼5 ps pulse width) and a continuous-wave (CW) seed laser are polarization controlled (PC) to minimize the reflected power at a polarizing beamsplitter (PBS). The pump is attenuated initially to the point where self-phase modulation can just be observed, with the pump wavelength redshifted by ∼3 nm from the HNLF zero-dispersion wavelength of 1542 nm; the seed power is around 12 dBm at the first HNLF input. The seed and the pump (spectrum shown in the top left of Fig. 1) are injected into a 98 m long link of HNLF to create pulsed pump, probe, and conjugate light with correlated phases (top middle Fig. 1), through the process of pump-degenerate four-wave mixing. The HNLF output is then sent to a pulse shaper which filters out the seed light as well as defines the probe, pump, and conjugate passbands (Fig. 1 upper right). The pulse shaper also compensates the chromatic dispersion of the system and is used to apply relative phase to each of the three frequency bands before injection into a second, 510 m link of identical HNLF. The common-spatial-mode nature of our interferometer ensures passive phase stability, with no need for active locking. However, unlike our intrinsically stable free-space version [9], the link loss between HNLF passes is significant here (∼4.9 dB), so that the reduced pump power would prevent equal gain in a second pass through the same length of HNLF. To maintain

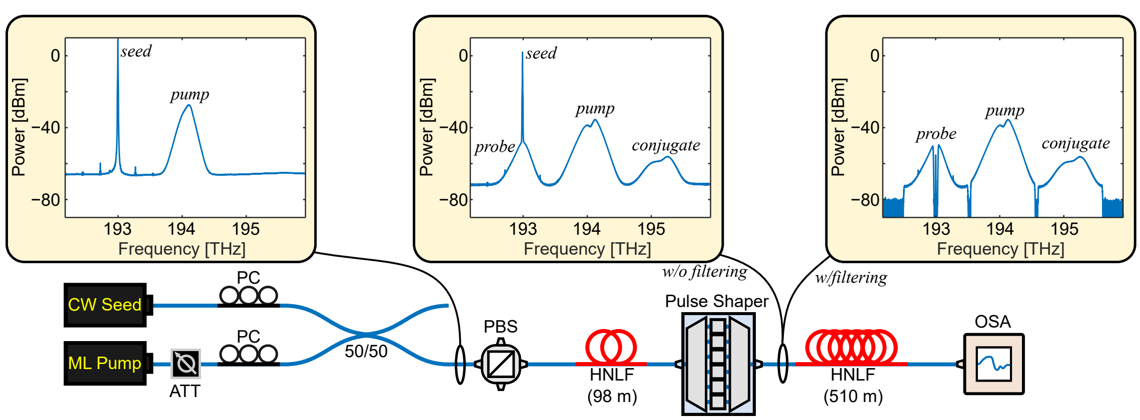

Fig. 1. Experimental setup (see text for details).

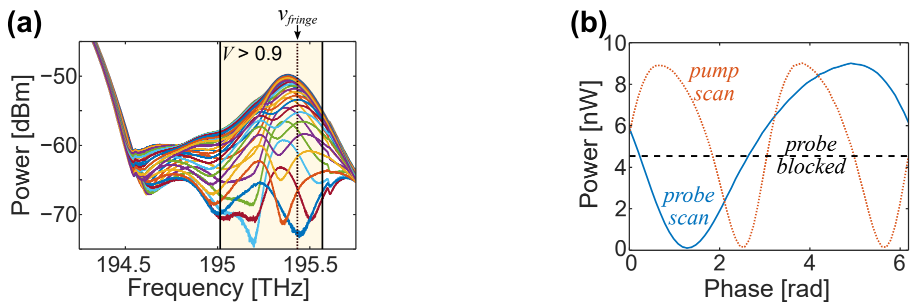

Fig. 2. (a) Measured conjugate spectra for various phases. (b) Interference fringe for ν_{fringe}.

high gain without separating and amplifying the pump (thus sacrificing passive stability), we enlist a proportionally longer link of HNLF for the second beamsplitter. The maximum possible parametric gain of an HNLF-based nonlinear beamsplitter is determined largely by the product of the fiber nonlinearity (γ), the pump power (P, in this case, the peak power) and the nonlinear fiber length (L). Our chosen fiber-length mismatch keeps γPL approximately constant, so the action of the nonlinear beamsplitters behave similarly [12]. The output of the 510 m long HNLF is measured with an optical spectrum analyzer (OSA). Our novel mismatched fiber-length approach provides a generally valuable tool for the development of stable, fiberized SU(1,1) phase sensors in lossy environments.

Instead of adjusting either nonlinear splitter independently, we optimize the overall performance of the system. The wavelength of the seed as well as the wavelength and power of the pump are scanned to attempt to maximize the interferometer's visibility and the phase-sensitive gain in the longer fiber. Figure 2(a) plots the measured conjugate output spectra for 32 different probe phase settings from 0 to 2π. The experimental response is qualitatively similar to numerical simulations generated using the split-step Fourier method. Vertical slices of Fig. 2(a) correspond to the measurement of an interference fringe within the $\sim$2 GHz spectral resolution of the OSA. The shaded area shows the 554 GHz bandwidth where the visibility is $>$90%.

The interference fringes at ν_{fringe} (195.433 THz) marked on Fig. 2(a) are plotted in Fig. 2(b). The plotted frequency has 15 dB of phase-insensitive gain and an additional 3 dB of phase sensitive gain in the second parametric amplifier. The measurement of the corresponding phase sensitivity is in progress. The asymmetric shape is qualitatively in agreement with numerical simulations. The raw visibilities for the two fringes in Fig. 2(b) are 0.976 when the probe phase is scanned and 0.967 when the pump phase is scanned. As expected for degenerate-pump four-wave mixing, the pump phase-scan period is half of the probe phase-scan period. Note that no effort was made to integrate only during the pulse duration, so it is possible that the visibility may be improved by measuring at a radio frequency harmonic as in reference [9].

In summary, we have described a novel SU(1,1) interferometer constructed with fiber optical parametric amplifiers. With high gain and $>$97% visibility, this platform promises to find application in distributed sensors.

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12. Strictly speaking, the gain is also a function of the pump wavelengths and their relationship to the zero dispersion wavelength of the HNLF as well as the pump power, so this is just an approximate starting point.