Long-distance frequency-division interferometer for communication and quantum cryptography

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We introduce and demonstrate experimentally a single-channel long-distance interferometer that utilizes frequency division of two optical waves by using acousto-optic devices at the transmitting and receiving nodes of the interferometer. This novel single-channel long-distance interferometer provides unity visibility of the interference and therefore is useful not only for remote sensing and optical communications but also for quantum cryptosystems applications.

A long-distance interferometer (LDI) is a device that provides interferometric interaction between transmitter and receiver nodes in remote locations. It allows a phase information coded beam and the reference beam from a transmitter node to be transmitted to a remote receiver node. For practical considerations, to ensure preservation of the fields' coherence properties that are necessary for detection it is desirable to use a single long-distance channel, in which the two optical fields are multiplexed and demultiplexed at the transmitter and the receiver nodes.[1,2]

LDI's have been used for high-sensitivity detection of phase information in physical processes that occur in a remote location[2] as well as for optical communication network applications.[1] Another application of a single-channel LDI is in secure optical communication that uses such principles of quantum cryptography[3,4] as polarization encoding (division) or time division[5,6] or a combination of polarization division and time division.[7,8] The quantum cryptosystems[5–8] use LDI's for the transmission of single photons. The states of the photons are selected randomly at the transmitting node from two conjugated bases by the use of orthonomal polarizations or phases, and at the receiving node one of these two conjugated bases is again selected at random for detection. When the selection of the basis at the receiver matches that used by the transmitter, the detection corresponds to probability 1; when the bases mismatch, the detection corresponds to probability 1/2. A prearranged protocol is used for translation of encrypted signals through an open channel. Operators at the transmitter and the receiver nodes develop a sequence of codes that can be used later for secret key encryption. The implementation of the quantum crypotosystem relies on the ability to detect single-photon interference effects. Inasmuch as for each photon the observation can be realized only once, a LDI with unity visibility of interference pattern is necessary to ensure that when one of the two conjugated bases at the receiver is selected correctly the detection will correspond to probability 1.

The existing techniques of implementing LDI's use time division, coherence division, or polarization division of two beams in a single communication channel. In the case of coherence division or time division a LDI can be realized by use of two unbalanced Mach–Zehnder devices communicating via a single transmission channel. The device at the transmitter node creates a time delay between the two beams that is greater than the coherence time[1,2] or the pulse duration[5,6] of the radiation. The device at the receiver node compensates for this time delay for two of the total of four optical signals and creates their interference at the output. For the coherence-division technique, because of the inevitable existence of a noninterfering signal the maximum visibility of interference is 1/2, which is nevertheless sufficient for remote sensing and communications. However, for the time-division LDI, interference with unity visibility can be obtained by use of time-resolved (time-gated) detection to isolate the two interfering optical signals from the two noninterfering signals.[5,6] A combination of time division and polarization division has been used to achieve high photon transmission efficiency,[7,8] which is important for quantum cryptography applications.

In this Letter we introduce a novel single-channel LDI that achieves frequency division of two optical waves by the use of acousto-optic devices in the transmitting and receiving nodes. Our single-communication-channel LDI provides unity visibility of the interference pattern and thereby is useful not only for remote sensing and optical communication but also for quantum cryptosystems applications. Frequency shift of radiation was used earlier in a LDI to provide heterodyne detection[2]; however, in this case unity fringe visibility can never be reached.

A schematic diagram of the frequency-division LDI is shown in Fig. 1. The interferometer consists of two Mach–Zehnder-type devices, one at the transmitter and the other at the receiver node, connected via a single optical communication channel. Each Mach–Zehnder device is implemented by an acousto-optic Bragg cell, a phase modulator, and a beam splitter. At the transmitter node a monochromatic beam of frequency ω is introduced into acousto-optic cell AOM1 driven at radio frequency (rf) Ω. The incident wave is separated into two equal-amplitude beams, transmitted and diffracted waves of frequen-

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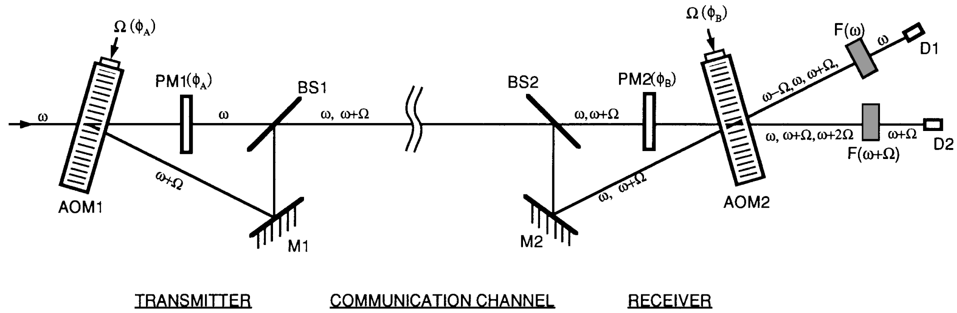

Fig. 1. Schematic diagram of the frequency-division long-distance interferometer. M's, mirrors.

cies ω and $\omega + \Omega$, respectively. The diffracted beam is transmitted through a phase modulator, PM1, to introduce a transmitter phase shift ϕ_A (this phase shift can also be introduced through the rf of AOM1). The transmitted and the diffracted waves propagate through different paths and are combined by beam splitter BS1 to implement frequency division. The resultant single two-frequency beam can be introduced into a long-distance optical communication link for transmission to the receiver node.

At the receiver node the beam from the communication channel is separated by beam splitter BS2 into two beams for demultiplexing and detection. These two beams, each containing waves at two optical frequencies, ω and $\omega + \Omega$, propagate through different paths, where one of the beams is transmitted through phase modulator PM2 to introduce the receiver phase shift ϕ_B (again, this phase shift can also be introduced via the rf of AOM2). Finally the two beams are combined by receiver acousto-optic cell AOM2 where each of the two incident beams is separated into equal-amplitude transmitted and diffracted waves. The two beams entering AOM2 need to be aligned such that the diffracted beam of one propagates in the direction of the transmitted beam of the other. Depending on the mutual direction of the two incident beams and the direction of propagation of the sound wave in AOM2, the diffracted beams will experience a frequency shift of Ω or $-\Omega$. The resultant output beams 1 and 2 will contain frequency signals of $\omega - \Omega$, ω, $\omega + \Omega$ and ω, $\omega + \Omega$, $\omega + 2\Omega$, respectively (see Fig. 1). Note that for precise compensation of the frequency shifts both the transmitter and the receiver acousto-optic cells need to be driven at the same rf, Ω.

After demultiplexing, only the waves of frequency ω in beam 1 and that of frequency $\omega + \Omega$ in beam 2 can produce interference signals. These two interference signals in beams 1 and 2 result from the superposition of optical fields that propagate through path AOM1, M1, BS1, BS2, PM2, AOM2 and through path AOM1, PM1, BS1, BS2, M2, AOM2, respectively. The resultant interference signals depend on the phase difference $\phi_A - \phi_B$, controlled by both PM1 and PM2, and therefore the transmitted information can be demodulated. These two output interference signals at frequencies ω and $\omega + \Omega$ are mutually complementary, similar to these of the conventional double-beam interferometer. In general, the two interference signals may be detected with two photodetectors, D1 and D2, but the maximum interference fringe visibility of such an interferometer will be limited to 1/2 because the presence of noninterfering frequency components. However, it is possible to achieve unity fringe visibility for the two interfering signals at frequencies ω and $\omega + \Omega$ by use of narrowband optical frequency filters $F(\omega)$ and $F(\omega + \Omega)$, respectively (see Fig. 1). Using monochromatic radiation and frequency division with frequency selection, as introduced in our LDI described above, is analogous to using short optical pulses and time gating in the LDI's with time division. Note that the introduced LDI can also be operated with a chaotic light source with a frequency bandwidth much larger

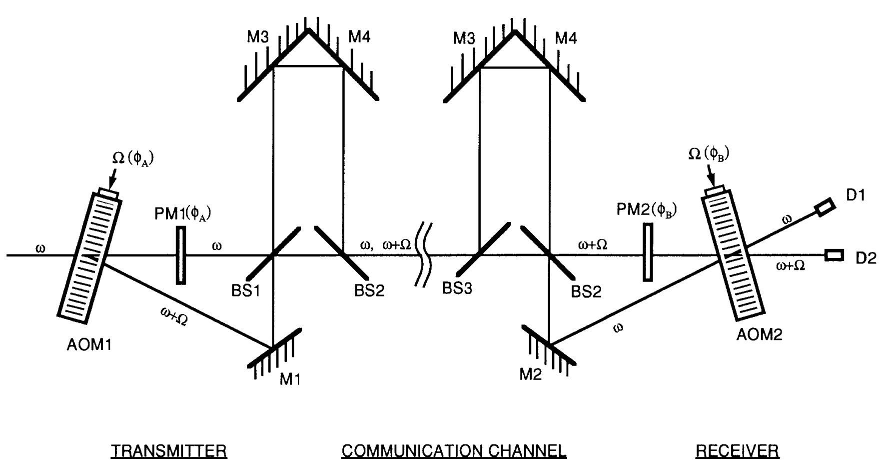

Fig. 2. Schematic diagram of the lossless frequency-division long-distance interferometer. M's, mirrors.

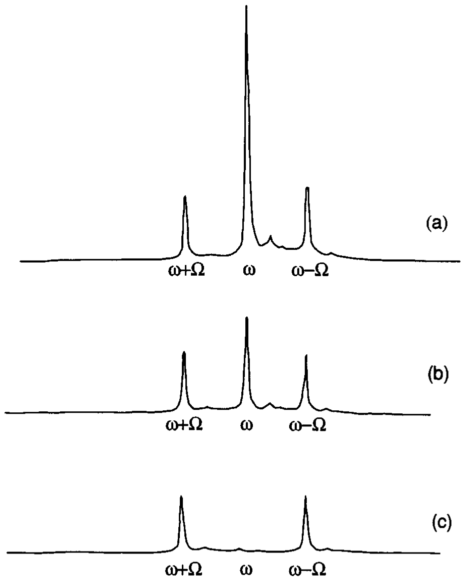

Fig. 3. Experimental results recorded at the output 1 of Fig. 1 by a scanning Fabry–Perot interferometer integrated with a photodetector: (a) $\phi_A - \phi_B = 0$, (b) $\phi_A - \phi_B = 2\pi/3$, (c) $\phi_A - \phi_B = \pi$.

than that of the acoustic frequency, which is analogous to using chaotic light for a time-division LDI.

An alternative scheme for LDI that produces interference fringes with unity visibility without energy losses is shown schematically in Fig. 2. In this approach BS1 and BS2 in the LDI of Fig. 1 are replaced by dichromatic interferometric beam splitters consisting of unbalanced Mach–Zehnder interferometers. The path difference in each interferometer is set to $L = \pi c/\Omega$. Such a path difference permits combination of the two beams of frequencies ω and $\omega + \Omega$ without loss into a single beam at the transmitter node and separation of a single dual-frequency (ω and $\omega + \Omega$) beam into two monochromatic beams at the receiver node.

We constructed and evaluated experimentally the performance and the LDI shown in Fig. 1. A monochromatic light source was used by a single-longitudinal-mode Ar^+ laser operated at a wavelength of 514 nm. Both acousto-optic Bragg cells (AOM1 and AOM2) were driven at a frequency of 83 MHz from the same rf source. The amplitudes of the acoustic waves were adjusted such that the intensities of the transmitted and diffracted (zero- and first-order) beams were equal. Free-space propagation was used as a single communication channel. The narrow-band optical frequency filter was realized by a scanning Fabry–Perot interferometer integrated with an output photodetector. During the scanning cycle of the Fabry–Perot interferometer all the three output frequency components were detected and introduced for display on an oscilloscope.

Figure 3 shows the experimental results registered by the scanning Fabry–Perot interferometer introduced at output beam 1 of the receiver. Three separate peaks represent the intensities at the three different frequencies, $\omega + \Omega$, ω, and $\omega - \Omega$. By adjusting the phase introduced by PM1 and PM2 we have demonstrated that the intensity of the center peak at frequency ω can be varied from a maximum [~3.6 times the side peaks in Fig. 3(a)] for $\phi_A - \phi_B = 0$ to a minimum [nearly zero in Fig. 3(c)] for $\phi_A - \phi_B = \pi$. The theoretical maximum and minimum values are 4 and 0, respectively, for unity contrast (100% visibility) from both output channels. Our result corresponds to 90% visibility. This deviation from the theoretical value is due to the fact that the acousto-optic cells and beam splitters are not perfect and therefore do not exhibit an exact 50/50 transmission and reflection ratio. Neither side peak is affected by the phase changes introduced from PM1 and PM2.

This frequency-division LDI possesses some advantages over existing LDI systems. Our system does not require high temporal resolution for photodetection or a polarization-preserved or -controlled long-distance communication channel. The disadvantage of the system is that it requires high-precision phase locking of two rf signals to achieve identical frequency shifts at both acousto-optical modulators.

In summary, we have introduced and demonstrated experimentally a single-channel LDI that uses frequency division of two optical waves using acousto-optic devices in the transmitting and receiving nodes of the interferometer. This novel single-channel LDI provides unity visibility of the interference pattern and thereby is useful not only for remote sensing and optical communications but also for quantum cryptosystems applications.

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