Optical phase noise engineering via acousto-optic interaction and its interferometric applications

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Abstract

We exercise rapid and fine control over the phase of light by transferring digitally generated phase jumps from radio frequency (rf) electrical signals onto light by means of acousto-optic interaction. By tailoring the statistics of phase jumps in the electrical signal and thereby engineering the optical phase noise, we manipulate the visibility of interference fringes in a Mach-Zehnder interferometer that incorporates two acousto-optic modulators. Such controlled dephasing finds applications in modern experiments involving the spread or diffusion of light in an optical network. Further, we analytically show how engineered partial phase noise can convert the dark port of a stabilised interferometer to a weak source of highly correlated photons.

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The fine control of optical phase shifts is of prime importance in numerous physical applications. On the one hand, interferometric measurements in fields as diverse as holography and gravitational wave detection demand precise compensation of random phase fluctuations arising out of environmental disturbances. On the other hand, quantum information and state manipulation demand deterministic phase shifts that are rapid and precise. A requirement that has recently emerged is that of controlled dephasing, critical in applications like optical implementation of quantum walks[1–3] and optical simulation of noise-assisted coherent transport[4] that seek to enhance the spread or diffusion of light in a network.

Light may be dephased by introducing random phase shifts in a variety of ways. An increase in the optical path length resulting in the phase shift of the emergent light may be effected on the milliseconds time scale, by means of the piezo-mechanical movement of an optical element or the use of liquid-crystal spatial light modulators and retarders. Recent quantum state manipulation experiments utilise electro-optic modulators[5] that typically respond in the \(\sim 10\mu s\) timescale or less; these not only are polarisation-sensitive but also have a limited range. An acousto-optic modulator (AOM) too may be used as a phase shifter, as shown by Li et al[6] with a resolution of \(6^\circ\), by Sadgrove et al[7] who imparted phase changes on time scales \(\approx 30\mu s\) and by Pandey et al, who utilised its polarisation insensitivity[3].

In this Letter we use appropriately tailored radio-frequency (rf) electrical input to impart random phase jumps to light via the acousto-optic interaction, at time intervals as short as 500ns and with a phase resolution of \(0.01^\circ\), thereby engineering any desired optical phase noise. We begin this Letter with a simple analysis of acousto-optically induced optical phase transfer from radio-frequency electrical signal, followed by its experimental demonstration in a Mach-Zehnder interferometer, that reveals the transfer of different phase shifts to the different orders of diffraction. The control of the visibility of fringes is demonstrated by using light with different phase noise statistics. Some possible applications are discussed. Finally, we analytically show how engineered partial phase noise can convert the dark port of a stabilised interferometer to a weak source of highly correlated, or bunched, photons.

In an AOM, an externally applied rf electrical signal of frequency \(\Omega_{rf}\) creates an acoustic strain wave of the same frequency and of wavelength \(\Lambda_s\).[8] The accompanying refractive index change, proportional to the amplitude of the strain, thus creates a moving grating that diffracts light of wavelength \(\lambda\) and frequency \(\omega\) according to the grating equation, which in
the Fraunhoffer limit is \( \Lambda_s (\sin \theta_i + \sin \theta_n) = n \lambda \), where \( \theta_i \) and \( \theta_n \) are the angles of incidence and diffraction of light, and \( n \) is the order of diffraction. As the grating is moving with velocity \( V_s = \Omega_{rf} \Lambda_s \), the \( n^{th} \) order diffracted light suffers a doppler shift and has a resulting frequency \( \omega_n = \omega (1 + n (V_s / \Lambda_s) (\lambda / c)) = \omega + n \Omega_{rf} \). Thus the frequency of the diffracted light in the different orders are shifted by integral multiples of the applied radio frequency.

The angle of diffraction is determined by the wavelength of light and that of the acoustic wave, while the diffraction efficiency is determined by the rf power. A phase shift of \( \phi_{rf} \) to the acoustic wave would effectively shift the grating in space by an amount \( \delta_s = \Lambda_s \phi_{rf} / 2\pi \) leading to a change in the path length of the \( n^{th} \) order diffracted beam by

\[
\delta \lambda_n = (\sin \theta_i + \sin \theta_n) \delta_s = n \lambda \phi_{rf} / 2\pi
\]  

The corresponding phase shift \( \phi_n \) imparted to the \( n^{th} \) order diffracted light beam is \( n \phi_{rf} \).

It may be noted that different orders acquire different phase shifts, that may be positive or negative, depending on the geometry.

As changes in phase of light can be seen only in interference, a Mach-Zehnder interferometer, with an AOM inserted in each of the two paths of the interferometer, was used to study the transfer of phase jumps from the rf signal to light via the acousto-optic interaction. Light from an external cavity diode laser at 767nm was divided into two equal parts at BS1 (Fig. 1). These were incident on acousto-optic modulators (Isomet) AOM1 and AOM2 that were aligned such that the light intensity was distributed into the diffraction orders \( n = -1, 0, 1, 2 \). The corresponding orders of the diffracted light from the two arms of the interferometer were combined at beamsplitter BS2. Light emerging from one exit port was incident on a screen where the interference patterns of all the four orders could be viewed. Light emerging from the other port was made incident on photodetectors \( D1 \) to \( D4 \) that measured the resultant intensities of the interfering diffracted beams of different orders, at a given fringe position. Digital frequency synthesizers (Toptica) VFG1 and VFG2 operating at 80 MHz, followed by radio-frequency amplifiers RFA1 and RFA2, were used to drive the two AOMs. In order to obtain stable fringes the digital rf signal generators were frequency locked using a 10MHz reference clock signal. The digital rf signal generator, based on DDS (direct digital synthesizer) technology in a FPGA (frequency programmable gate array) platform, has a frequency resolution of \( \sim 50 \text{mHz} \) and a phase resolution of \( \sim 0.1 \text{mrad} \), and permits changes on a time scale of \( 500 \text{ns} \) (sustained) and even \( 5 \text{ns} \) (brief). The entire
FIG. 1. (Color online) Schematic of the experimental setup

FIG. 2. (Color online) Detector recordings of the intensity of interference at a fixed location for various orders of diffracted light when (a) PZM2 is oscillated at $2.5\, \text{Hz}$, and (b) the phase of the rf is ramped from $0^\circ$ to $360^\circ$ at $2.5\, \text{Hz}$.

experiment was set up on a vibration isolation optical table and shielded from air-drafts. Interference patterns were stable over $\sim 1\, \text{s}$. Mirror $M1$ and piezo operated mirror $PZM2$ were adjusted such that line fringes were seen on all the orders. Detectors $D1$ to $D4$ had active areas smaller than a fringe width, so that any shift of a fringe, say by the introduction of an additional phase shift, was recorded as a change in the detector signal.

In contrast to mechanical disturbances, that cause the same amount of phase shift to the undiffracted light and light that is diffracted to various orders, the acousto-optically imparted phase shifts affect the various orders to different extents. Oscillation of mirror $PZM2$ by means of a $2.5\, \text{Hz}$ ramp voltage showed that fringes of all orders oscillate in
unison, at the same frequency as the ramp voltage and in phase (Fig. 2a). Next VFG1 was programmed to generate an rf signal of 80MHz with a superposed digital phase ramp from 0° to 360° (10^4 samples) which was then amplified and fed to AOM1, while AOM2 received just the 80MHz rf. The signals recorded on the photodetectors D1 to D4 (Fig. 2b) showed that the undiffracted 0th order remained unaffected; the 1st order oscillated at the same frequency as the phase modulation of the rf signal; the −1st order oscillated at the same frequency, but exactly out of phase with the 1st order beam; and the 2nd order oscillated at twice the frequency, exactly as expected from the earlier analysis.

This technique of changing the phase of light through acousto-optic interaction makes possible the creation of a light source with phase noise alone - a kind of source considered theoretically by Baym [9], and recently realized by Satapathy et al in a different context [10]. We examined this by supplying rf electrical signal with abrupt phase jumps of random values to AOM1 at intervals of 500ns (Fig. 3(a)). These resulted in abrupt fringe shifts causing a sudden change in the detector signal level from one quasi-stable value to another (Fig. 3(b)). The single beam intensity measured by detector D5 prior to the interference, however, remained essentially constant (Fig. 3(c)), confirming that a phase change to the rf alters only the phase of the diffracted light and not its intensity. The small glitches (∼ 50ns; limited by bandwidth of our photodetector) seen both in the single beam intensity and the two-beam interference signals arise predominantly due to the fact that at the instant of the abrupt phase changes, the frequency spread of the rf and consequently the angular spread of the diffracted light is large. The ∼ 100ns lag observed between the phase jump in the rf and the shift in detector signal level is attributed to the slow speed of the acoustic strain wave within the AOM crystal.

By tailoring the amplitude and the statistical distribution of the phase jumps, light with different phase noise statistics and varying extents of dephasing may be created. We use this technique to demonstrate the control of the visibility of interference fringes. Long sequences of computer generated psuedo-random numbers of various statistical distributions of phase jumps (with 0.01° resolution) were fed to VFG1 that was then programmed to generate a 80MHz rf signal with its phase altered in that fashion. The parameters amenable to manipulation were the functional form of the probability distribution, the mean residence time, and the amplitude of phase excursions. The rf signal was fed to AOM1 and the interference pattern of the 1st and 2nd order diffracted light recorded with a CCD camera...
FIG. 3. (Color online) (a) The rf signal with abrupt phase jumps, that was fed to AOM1, (b) the interference signal recorded using the $-1^{st}$ order diffracted light (D1), and (c) the intensity of a weak pick-off beam from the $-1^{st}$ order diffracted light (D5).

(Watec, 25 fps). Fig. 4(a) shows the images recorded for a uniform distribution of amplitude of phase jumps, for various standard deviations and Fig. 4(b) the same for a gaussian distribution. For a perfectly coherent source, and equal intensities of the interfering beams, $V = 1$. In the presence of phase noise the visibility of $n^{th}$ order fringe $V_n = \langle \cos(n\phi) \rangle$, where $\phi$ is the random rf phase difference between the two AOMs. For a uniform distribution of rf phase jumps in range $-\alpha \leq \phi \leq \alpha$,

$$V_n(\alpha) = \left| \frac{1}{2\alpha} \int_{-\alpha}^{\alpha} \cos(n\phi) \, d\phi \right| = \left| \frac{\sin(n\alpha)}{n\alpha} \right|$$  \hspace{1cm} (2)

and for a gaussian distribution of standard deviation $\sigma$,

$$V_n(\sigma) = \left| \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\infty} \cos(n\phi)e^{-\frac{\phi^2}{2\sigma^2}} \, d\phi \right| = e^{-\frac{n^2\sigma^2}{2}}$$  \hspace{1cm} (3)

The average relative visibility $(V_n(\alpha \text{ or } \sigma)/V_n(0))$, determined experimentally from a set of 50 images of interference patterns of the $1^{st}$ and $2^{nd}$ order diffracted light, are shown as circles in Fig. 4(c) and (d) for various parameters of uniform and gaussian phase noises, respectively. They match quite well with the theoretical curves obtained from Eqs. 2 and 3. This effectively demonstrates the controlled dephasing of light using AOMs. In contrast to EOM-based dephasing that suffers from a voltage limit and therefore to a phase-jump limit, the use of an AOM does not impose a restriction on the amplitude of the phase jump.

Dephasing or phase noise has traditionally been sought to be eliminated. However, contrary to belief, noise has recently been shown to be beneficial in certain situations like white
FIG. 4. (Color online) Interference patterns recorded for the 1st and 2nd order diffracted light for various parameters of (a) uniform, and (b) gaussian distributions of phase jumps; (c) and (d) are the visibilities extracted from the data (dots) shown along with the theoretically expected curves. The error bars (standard deviation) are mostly within the circles.

noise induced entanglement of light [11, 12], noise-assisted enhancement of channel capacity in the transmission of classical and quantum information [13] and the more uniform spread of the quantum walker under partial decoherence [14]. Currently the role of dephasing in photosynthesis and in increasing the efficiency of solar energy harvesting complexes is under intense investigation [15–17]. Underlying the photonic implementations and simulations of these phenomena is the multistage interference of light [1–4]. Our work opens up the possibility of introducing phase noise of the desired statistics in a controlled fashion which could lead to the optimization of the noise-induced effects in such systems.

Using the technique of introducing controlled phase noise in an interferometer, we arrive at an interesting result in a completely different context - the creation of a weak source of highly correlated photons. Let us consider again the interferometer of Fig. 1 that has been perfectly aligned and stabilized with a phase difference $\theta \sim 0$ between two arms, such that one port is nearly dark (-) and the other port bright (+). With phase noise introduced in one of the AOMs, instantaneous intensities at the two exit ports would be given by $I_{\pm}(t) = I_0[1 \pm \cos(\theta + \phi(t))]$ where $I_0$ is the intensity of the first order diffracted light at each AOM. The second order correlation or intensity-intensity correlation of the light emerging from two exit ports, is $G_{2,2}^2(\tau) = \langle I_{\pm}(t)I_{\pm}(t+\tau) \rangle_t / \langle I_{\pm}(t) \rangle_t^2$. The zero delay second order
The correlation is,

\[ G_\pm^2(0) = 1 + \frac{(\cos^2(\theta + \phi(t)))_t - (\cos(\theta + \phi(t)))_t^2}{(1 \pm \cos(\theta + \phi(t)))_t^2} \]  

(4)

For uniform phase noise in the range \(-\alpha \leq \phi \leq \alpha\) being fed to AOM1,

\[ G_\pm^2(0) = 1 + \frac{1}{2} \left( \cos(2\theta) \frac{\sin(2\alpha)}{2\alpha} + 1 \right) - \cos^2(\theta) \frac{\sin^2(\alpha)}{\alpha^2} \]

(5)

while for gaussian phase noise of standard deviation \(\sigma\),

\[ G_\pm^2(0) = 1 + \frac{1}{2} \left( \cos(2\theta) e^{-\frac{2\sigma^2}{2}} + 1 \right) - \cos^2(\theta) e^{-\frac{2\sigma^2}{2}} \]

(6)

For complete phase noise i.e., when \(\alpha = n\pi\) or \(\sigma = \infty\), we see from eqns 5 and 6 that \(G_\pm^2(0) = 1\). Similarly in the absence of phase noise i.e., when \(\alpha\) or \(\sigma\) is 0, \(G_\pm^2(0) = 1\) for all \(\theta \neq 0\). The case \(\theta = 0\) i.e one port completely dark and the other maximally bright, is interesting and needs further elaboration. For \(\theta = \alpha = \sigma = 0\), \(G_-^2(0)\) is, mathematically speaking, undefined. However this may be evaluated in two ways in the vicinity of \(\theta = 0\). Fixing \(\alpha\) (or \(\sigma\)) equals to zero and then taking the limit on \(\theta\) one gets the value \(G_\pm^2(0) = 1\), the value that one obtains for a coherent source. Instead, fixing \(\theta = 0\) and taking the limit of \(\alpha\) (or \(\sigma\)) tending to zero, one obtains \(G_-^2(0)\) equals to 1.8 (3). The latter may be physically understood as the dark port of a well stabilized Mach-Zehnder interferometer becoming a weak source of highly correlated or bunched photons in the presence of a small engineered phase noise, with the value of correlation depending on the nature of the phase noise. Interestingly, as \(G_\pm^2(0)\) remains nearly 1 in the presence of small phase noise, there is negligible loss of coherence in the light emerging from the bright port. In Fig.5 \(G_\pm^2(0)\) are plotted for various values of \(\theta\) close to zero to show how the limit is approached. It can be seen that for uniform phase noise \(G_\pm^2(0)\) attains a maximum (\(> 2\)) for \(\theta\) close to, but not equal to, 0.

Recently, higher order intensity correlations have been resorted to for the enhancement of contrast in ghost imaging using thermal light [18–21]. However, this has a limiting value of \(N!\) for the \(N^{th}\) order correlation; this limit is 2 for second order intensity correlation [21]. As shown in Fig.5 \(G_-^2(0)\) exceeds the value 2 for a range of parameters of uniform and gaussian phase noise. In fact, dramatic enhancement results even for the second order correlation if one were to impart phase noise having the Lorentzian (Cauchy) probability
distribution function \( \pi \gamma \left( \frac{(x-\theta)^2}{\gamma^2} + 1 \right)^{-1} \), with a noise parameter \( \gamma \). For \( \theta = 0 \), we have \( G_{\pm}(0) = 1 + \frac{1}{2} \frac{(1\pm e^{-\gamma})}{(1\pm e^{-\gamma})} \). In the limiting value of \( \gamma \to 0 \), \( G_{-}(0) \) diverges, suggesting that very high values of correlation can be obtained with a small amount of engineered Lorentzian phase noise.

As described earlier, in the interferometer of Fig. 1, all orders of diffracted light are seen to suffer the same phase shift on mechanical vibrations, but different amounts due to acousto-optic interaction. This could be made use of in introducing rapid and precise partial dephasing of light. For this, the 0\(^{th}\) order fringe should be used for stabilisation of the interferometer against uncontrolled environmental fluctuations by conventional techniques (like feedback to the piezo), while engineered phase noise is introduced to the AOM to dynamically dephase the diffracted light in a controlled fashion.

To conclude, we have shown how an AOM may be used to impart phase noise of desired characteristics to light in a rapid, controlled and precise manner. This allows for controlled dephasing of light; an important feature is optimizing several light transport based phenomena. We have also shown the possibility of creating (weak) sources of highly correlated photons using a balanced Mach-Zehnder interferometer with engineered partial phase noise. The ability to control both the interval between phase jumps and the amplitude of phase jumps opens up the possibility of creating classical, incoherent light sources with tunable
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