An Acousto-Optic Modulator Based High Performance Optical Switch for Quantum Technology in Fiber Communication Band

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Abstract: We demonstrate an optical switch based on the interferometric enhancement of acousto-optic diffraction. The high transmitting efficiency of 92% and the high isolation of 74 dB make it a powerful tool for quantum technology.

In Quantum optical technology, Acousto-optic modulators (AOMs) are frequently used as an optical switch. Current commercial AOMs have a diffraction efficiency larger than 85% per pass with the constrain of input beam size and driving power. While this efficiency is enough for most of the classical applications, it is still not high enough for the quantum applications where quantum states have to transmit through the AOMs and keep the high efficiency. This impels us to consider the interferometric enhancement of the diffraction effect when using AOMs as a switch for quantum state. In Ref. [1], an AOM is used as a beam-splitter to implement photon heterodyning. Recently, Ref. [2] reports an interferometer scheme using AOMs as the beam-splitter and the beam-combiner to observe the beating signal of single photons. Here we demonstrate a high performance optical switch for quantum technology based on a bi-frequency interferometer using AOMs as the beam splitter/combiner. The beating signal has a near prefect visibility of $(99.5 \pm 0.2)\%$. The interferometer can stably work in arbitrary phase with a dither phase locking system in chopped locking mode [3], and the minimum locking duty cycle is as small as 30%. These features enable us to realize a high performance optical switch with transmitting efficiency of 92% and intensity isolation of 74 dB in fiber communication band.

The principle of AOMs working as a beam splitter/combiner is shown in Fig.1(a). When two optical fields a_{ω_1} and b_{ω_2} are aligned to the -1st order and the +1st order of Bragg diffraction with driving frequency of Ω, the output fields c and d have the form of

$$\begin{aligned} c &= \quad tb_{\omega 2} + e^{i\theta} ra_{\omega 1-\Omega} \\ d &= \quad ta_{\omega 1} - e^{-i\theta} rb_{\omega 2+\Omega}, \end{aligned} \tag{1}$$

where t, r are the splitting parameters and θ is AOM induced phase. In the particular case of $\omega_1 = \omega + \Omega$ and $\omega_2 = \omega$, the output from an AOM only contains the optical field with frequency ω or $\omega + \Omega$.

Following the idea of combining the same optical frequency in the same spatial mode, we experimentally build an AOM based interferometer as in Fig.1(b). A linearly polarized optical field at fiber communication band of 1550.12 nm band (b_ω) is coupled to the +1st Bragg mode of AOM_1, and the other input port of AOM_1 leaves vacuum ($a_\omega = 0$). When the driving RF signal of AOM_1 is on, the injected optical field is splitted into a frequency up-shifted arm ($d'_{\omega+\Omega}$) and a non-shifted arm (c'_ω). For each arm, two plane mirrors and a concave mirror (CM) with 300 mm radius of curvature are used to guide the laser beam to the AOM_2, where c'_ω and $d'_{\omega+\Omega}$ are aligned to the +1st order and the -1st order of Bragg diffraction of AOM_2. The final output amplitude of the interferometer can be obtained by using Eq. (1) twice, and reads:

$$\begin{aligned} e_{\omega+\Omega} &= \quad \left[r_1 t_2 e^{i(\varphi-\theta_1)} + t_1 r_2 e^{-i\theta_2}\right] b_{\omega+\Omega} \\ f_\omega &= \quad \left[t_1 t_2 - r_1 r_2 e^{i(\theta_2-\theta_1+\varphi)}\right] b_\omega, \end{aligned} \tag{2}$$

where φ is the phase difference between the two arms of the ABI, $t_{1,2}$, $r_{1,2}$ and $\theta_{1,2}$ are the splitting parameters and acoustic modulation induced phase of AOM_1 and AOM_2, respectively. To control the phase between two arms and realize phase locking, a piezo device (PZT) is mounted on the concave mirror of the frequency up-shifted arm. At the output of the AOM_2, the intensity of the frequency up-shifted port is detected by a photo diode (PD). By tuning the power of RF signals applied to AOM_1 and AOM_2, the splitting ratio of the AOM is set to be $t_{1,2}^2 = r_{1,2}^2 = 0.5$. The ideal output intensity of the AOM-based interferometer can be obtained by using Eq. (2)

$$I_{out} = e^*_{\omega+\Omega} e_{\omega+\Omega} = \frac{1}{2}\left[1 + \cos(\phi)\right] I_{in}, \tag{3}$$

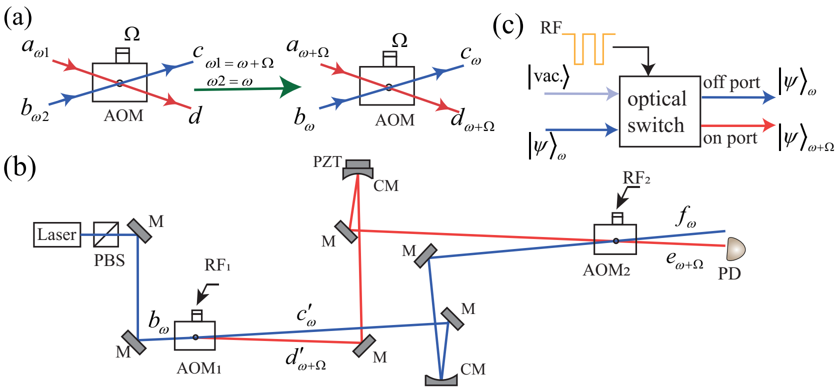

Fig. 1. (a) The optical frequency shifting property when an acusto-optic modulator (AOM) is used as a beam splitter/combiner. (b) The experimental setup of the AOM based interferometer we realize. (c) Illustration of the AOM based interferometer used as a high efficiency and high isolation switch for optical quantum state with chopped RF driving signal. PBS, polarization beam splitter; AOM, Acousto-optic modulator; CM, concave mirror; M, plane mirror; PZT, piezo-electric translation device; PD, photo diode.

where $\phi = \varphi - \theta_1 + \theta_2$ is the phase difference between two arms, $I_{in} = b^*_\omega b_\omega$ is the intensity of the input light. Since the intensity summation of the two output ports is an invariant, the intensity at the other port can be deduced accordingly and is not presented in the paper. In the experiment, we consider three practical parameters: (i) the non-ideal efficiency η of the optical components, (ii) the mode mis-matching induced non-ideal visibility V of the interference, and (iii) the beat between the two RF driving signals. With these parameters considered, Eq.(3) is rewritten as

$$I'_{out} = \frac{\eta}{2}\Big[1 + V\cos(\Delta\omega T + \phi)\Big] I_{in}, \tag{4}$$

where $\Delta\omega$ is the angular frequency difference of the RF signals and T is the time variable.

The interferometer we describe can be used as a high efficiency high isolation optical switch controlled by the radio frequency signal (RF). As it is shown in Fig.1(c), if a quantum state $|\psi\rangle_\omega$ is sent to the input port b_ω, then the output "on" and "off" ports correspond to $e_{\omega+\Omega}$ and f_ω in Fig.1(b). To set the optical switch to "off" state, we completely shut down the RF signals which drive the AOMs, and the optical path of the interferometer is degraded into free propagating spatial modes. By doing this, the intensity isolation of the "off" state is high and is not confined by the imperfect visibility of the interference. To set the optical switch to "on" state, we make RF_1 and RF_2 to be identical frequency of 80 MHz to enable the interference process, and the phase of the interferometer is controled by the PZT in Fig.1(b). To compensate the phase drifting caused by the environment, a dither phase locking [3] algorithm is implement with the PyRPL phase locking software package [4] running on a FPGA board (STEMLab125-14). To make the setup simplier and have higher efficiency, the phase dithering signal is added onto AOM_1 with a 200 kHz phase modulation to the RF_1 signal, so no extra optical component for phase dithering generation is necessary. We note our optical switch scheme will also introduce a frequency shift of 80MHz to the input light due to acousto-optic diffraction effect when set to the "on" state.

During the experiment, we measure the intensity I'_{out} at one output in different cases, In order to analyze the results conveniently, I'_{out} is normalized to the intensity of input field I_{in} which shows the efficiency of our device. Firstly, we demonstrate the beating signal, and calibrate the visibility of the interference V and the optical efficiency η by fitting the data to Eq. (4). The frequency of the signal RF1 and RF2 are 80 MHz and 79.9 MHz, and thus the beat frequency $\Delta\omega/2\pi$ is set to 100 kHz. With careful alignment, we obtain a beating signal with near prefect visibility, as the result shown in Fig.2(a). By fitting the data to Eq. (4), the interference visibility and the non-ideal efficiency of the optical components are estimated to be V=$(99.5\pm0.2)\%$ and η=$(95\pm1)\%$, respectively. We note each optical surface in our experimental setup has a loss of about 0.5% limited by the quality of optical coating, so η can be further improved once components with better optical coatings are used.

In the next, we set RF_1 and RF_2 to be identical frequency of 80 MHz. By scaning the PZT with a ramp signal and examining the interference fringe, we find the visibility of interference for the identical frequency case is reduced to 93.7%, which corresponds to the total transmission efficiency of the optical switch is 92% when the interferometer is locking to the maximum working point. We study the reason for this visibility reduction and find, besides a phase shift, the PZT can cause the beam walking-off and will therefore induce mode mis-matching. This indicates the visibility in identical frequency driving mode can be further optimized by removing the PZT and introducing phase shift by AOM_2 in Fig.1(b). To complete this optimization, angle calculation and phase

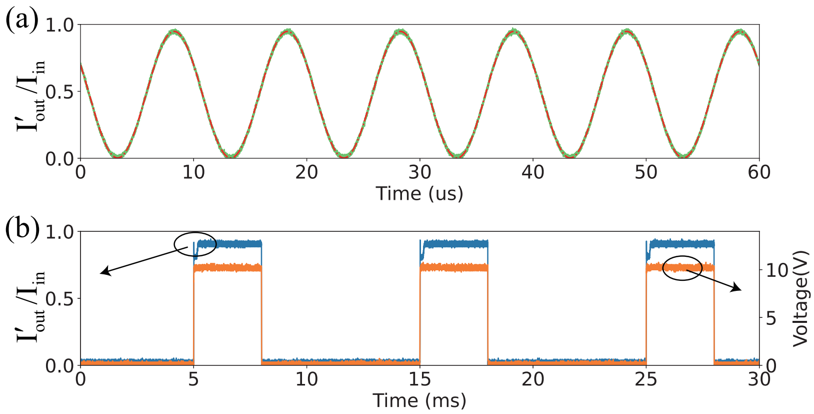

Fig. 2. Experimental result. (a) Beating signal when two AOMs are driving in a RF frequency difference of 100 kHz: green trace, directly measured beat signal; red dash-dotted line, fitting of the beating signal. (b) Single port output intensity of the optical switch in chopped phase locking mode with a locking duty cycle of 30%.

unwrapping algorithms are necessary to be implemented in the FPGA and the progress is underway.

With the experimental method above mentioned, we demonstrate the optical chopping ability of the optical switch, and the result is shown in Fig.2(b). In this specific working setup, The RF_1 and RF_2 in Fig.1(b) are periodically turned on and off by a 100 Hz electronic gate pulses with 30% duty cycle (shown in Fig.2(b) by the orange trace) and the phase locking system is set to lock to the maximum intensity. The intensity measured at the ”on” port is shown with the blue trace in Fig.2(b). when the gate pulse is on, one sees a phase locking establishing time of about 0.2 ms is needed, but the normalized intensity is stably stay at around 0.92 for the rest of the time. This result indicate our setup can be used as a high efficiency optical switch to transmit a quantum optical state with very few average photon number in 70% of the time, and only use 30% of the time to control the phase of the setup. We further analyze the isolation property of the AOM based optical switch. We couple the free space light from the frequency up-shifted output port of AOM_2 into a single photon detector (id Quantique-id200) working at gated mode of 1 MHz triggers per second. By comparing the photon counting result of on and off state, we find the isolation of the system equals to 74 dB, which shows the AOM based optical switch has a high degree of isolation.

In summary, we have demonstrated an optical switch based on the interferometric enhancement of acousto-optic diffraction. The high transmitting efficiency of 92% and the high isolation of 74 dB make it a powerful tool for quantum technology in fiber communication band.

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