A high-power spectral beamsplitter for closely spaced frequencies

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An experimental realization of a compact, high-power spectral beamsplitter for nearly equal frequencies and identical polarization based on two-beam interference in a free-space Mach-Zehnder interferometer is presented. We demonstrate the power- and cost-efficient generation and subsequent spatial separation of two laser tones from a single sum-frequency-generation stage using double-sideband suppressed-carrier modulation in the infrared, and beam splitting in the visible at high power. The interferometer spectrally splits \( >98 \% \) of the incident power when accounting for bulk absorption. The beamsplitter can be constructed identically for any power or spectral range required for which suitable optics are available.

I. INTRODUCTION

Precise control over the spectral and spatial properties of light is essential in various implementations of atomic physics, photonics, or quantum information processing based on trapped atoms and ions. In many of these applications multi-tone optical spectra with separations in the GHz range but otherwise identical properties are required. There are two major challenges arising when working with beams of closely spaced frequencies; Firstly, generation of such spectra can be cost inefficient and technically challenging, particularly if phase-coherence is required from independent sources; Secondly, splitting and recombination of spectral components at close frequency spacings can typically not be achieved with passive components whose discriminator slopes of a few nanometers width are many orders of magnitude too shallow for this task.

In this manuscript we present a power-efficient system for the separation (or combination) of GHz-spaced tones of identical polarization utilizing a Mach-Zehnder beamsplitter (MZ-BS) from a single, phase-coherent beam. We present details on the design and operation of the MZ-BS which operates at any power, optical frequency, or splitting for which suitable components are available. As a two-beam interferometer it does not require impedance or mode matching, performs best with convenient collimated input beams, and exhibits significantly relaxed length-stability requirements relative to alternative ring cavities. Taken together these advantages enable superior performance in terms of alignment simplicity and reduced susceptibility to acoustic pickup.

As a concrete example application, we demonstrate the generation and splitting of two phase-coherent laser tones separated by \( \approx 27.5 \text{GHz} \) for electromagnetically-induced transparency (EIT) cooling of 2D beryllium ion crystals in analog quantum simulation experiments. The cooling lasers are centered near \( 313 \text{ nm} \) and are generated by sum frequency generation (SFG) followed by resonantly-enhanced second harmonic generation (SHG). Our approach reduces laser complexity by generating two narrowly-spaced seed-laser colors in the infrared, leveraging mature telecommunications-band waveguide-based modulation schemes. This allows two tones near \( 626 \text{ nm} \) to be generated from a single SFG stage. We characterize the MZ-BS for beam separation in the visible near \( 626 \text{ nm} \) prior to frequency doubling, and demonstrate spectral splitting with \( >98 \% \) contrast (\( \approx 500 \text{mW per beam} \)), consistent with theoretical predictions for optical losses in passive elements.

II. MACH-ZEHNDER BEAMSLICITRER

The Mach-Zehnder beamsplitter (MZ-BS) is a Mach-Zehnder interferometer which is operated at a specific optical path length. In our implementation of the Mach-Zehnder interferometer, the input light is first split and then recom-
bined on two 50:50 beamsplitters forming a two-path interferometer (Fig. 1a). The amount of light of a given frequency exiting one of the two output ports in such an interferometer is a function of the optical-path-length difference between the arms, which is frequency dependent. For the task of separating two narrowly spaced spectral tones, the optical-path-length difference between the two arms is varied, here enabled by a movable folding prism in the long arm. This parameter can be tuned to ensure constructive interference for one of the two input frequencies and destructive interference for the other on the same output port (Fig. 1b). Designing the MZ-BS thus requires finding the interferometer dimensions that achieve this for a given frequency splitting. Given the geometric quantities defined in Fig. 1a we can find the optical path length difference between the arms as

$$\Delta r = 2L + nH - D,$$

where $n$ denotes the refractive index of the prism material, and we measure both $L$ and $D$ from the center of the cubes. For separating two spectral tones on one input beam (or its time-reverse of combining two single-tone beam inputs into one two-tone output) we find the optical phase difference between the two paths for each of the two tones as

$$\delta_1 = k_1 \Delta r$$

$$\delta_2 = k_2 \Delta r + \pi$$

$$\Delta k = k_2 - k_1 = 2\pi \Delta \nu/c,$$

where $k_i$ are the wave vectors of the two tones, $c$ is the speed of light in vacuum, and $\Delta \nu$ is the frequency splitting. Taking into account phase shifts upon reflection from higher to lower optical density we find for either configuration that the path difference for splitting/combination needs to be

$$\Delta r = \frac{c}{\Delta \nu} \left( N_2 - N_1 - \frac{1}{2} \right),$$

where $N_i$ are integer numbers. Generally, adjusting just one dimension of the interferometer, for example $L$, reduces complexity but is insufficient to guarantee complete interference in both frequencies at the same time; i.e. for arbitrary $k_i$ we cannot enforce both $N_i$ to be integers. However, there are always interferometer dimensions $L$ that produce negligible loss in contrast compared to the ideal case, owing to the small relative frequency spacing. We refer to these interferometer dimensions as $L_{\text{opt}}(\Delta \nu)$, since they maximize the simultaneously achievable contrast, with

$$L_{\text{opt}} = \frac{1}{2} \left( D - nH + \frac{c}{\Delta \nu} \left( N_2 - N_1 - \frac{1}{2} \right) \right).$$

The rough length scale for the desired beam splitting, that is $L_{\text{opt}}$ at $\Delta \nu$, is set with a micrometer stage displacing the folding prism, while adjustment on interferometric length scales is provided by a piezoelectric transducer (Fig. 1a). In our application the relative frequency difference is $\Delta \nu \approx 10^{-5}$ such that thousands of wave cycles need to be bridged by $L$ to tune the interferometer between in-phase and out-of-phase operation, far beyond the tuning range of the piezo. This means that $L$ typically has to be adjusted to within $\pm 1$ mm using the micrometer, in order to achieve high contrast.

Our implementation of a MZ-BS was constructed with a monolithic base having a footprint of $\approx 29 \times 17$ cm, as shown in Fig. 2 and is otherwise made from bulk components (Thorlabs and custom-machined). Roughly half of the surface area is taken by the interferometer, and the other half by a beam folding section which allows isolation of the feedback signal from other reflections in the optics. The interferometer itself is composed of a pair of non-polarizing beamsplitter cubes (BS007 and BS010, respectively sitting on FBTC and fixed holder) and a 20 mm right-angle prism (PS908H-A on a custom seat) which is moved by a piezo transducer (PA4HKW) to allow adjustment of the optical-path-length difference of the interferometer. The cube centers are separated by 21 mm and are positioned 13.5 mm from the front face of the prism. We opt to use a right angle prism with adjusters instead of a fixed roof prism or corner cube due to the superior transmission for high power operation.

The prism assembly further features alignment degrees of freedom through its mounting; translation via DT12/M dovetail stage; pitch and roll through KM100B/M kinematic
mount; and yaw through a custom mounting adapter. The required translation used to adjust the total interferometer length towards \( L_{\text{opt}} \) is accomplished using a MT1/M linear translation stage. Similarly we provide pitch, yaw, and roll adjustment capabilities for the BS007 cube through the FBTC cube holder in order to compensate for machining and assembly imprecision. Bulk optics were selected in convenient sizes for ease of operation and reduced cost; the setup can be significantly compactified by employing a custom chevron prism, a beamsplitter-coated right angle prism, and smaller detectors. The assembly features a removable lid to provide modest acoustic shielding and laser safety.

The interferometer length needs to be actively stabilized to maintain efficient operation. We derive an error signal for interferometer-length stabilization by generating a back reflection at one output port from a circular wedge prism (PS812) and sending it back through the interferometer. This back-reflected beam exits port 2 of the interferometer (Fig. 1a and Fig. 3) where it is directed to a photodiode. Only one of the frequency components will be present at each output port if the interferometer length is near \( L_{\text{opt}} \) and the piezo is set for complete interference. The backscattered, single-tone light will then see maximum destructive interference on the photodiode at port 2, minimizing the photodiode signal, which provides a dip-like error signal. Feedback is then implemented using a dither lock.

Alignment proceeds by optimizing the linear stage position while periodically scanning the path length using the piezo until the power on both output ports is constant irrespective of piezo voltage, thus fixing \( L \) near \( L_{\text{opt}} \). The back reflection from either output port is then aligned through the interferometer and onto the photodiode. If the interferometer is adjusted away from all \( L_{\text{opt}} \), the back reflection will not be spectrally pure, and the interference-fringe contrast on the photodiode will decrease.

III. EXPERIMENTAL SETUP

A schematic of the experimental setup used to efficiently generate and subsequently split the laser tones is shown in Fig. 3. Our laser system is based on a cascading nonlinear frequency conversion scheme that begins with commercial fiber lasers and fiber amplifiers feeding into a single-pass sum frequency generation setup converting light to the visible. High-power beam splitting is conducted in the red using the MZ-BS before visible light is fiber-coupled and fed to resonantly-enhanced second harmonic generation modules.

The two-tone laser spectrum is generated in the visible by modulation of a seed IR laser prior to amplification and SFG conversion to the red. We insert a commercial waveguide intensity modulator (IXblue MXER-LN-20-PD-P-P-F3-FA-30dB) between the seed and amplifier of a custom 1550 nm fiber laser (OrbitsLightwave INST-2500A-1549.60-5-PZ10B-TT60) providing direct fiber-based access to the seed light. The broadband modulator is driven by a microwave source at \( \approx 27.5/2 \) GHz and is biased to operate at the minimum of its transfer function to create only an upper (blue) and lower (red) sideband, while suppressing the carrier via double-sideband suppressed-carrier amplitude modulation (DSB-SC). This modulation scheme is advantageous as it minimizes power loss to the carrier or higher-order sidebands, and outperforms typical schemes involving a waveguide- or free space-electrooptic modulator and harmonic phase modulation. It is not necessary to stabilize this bias point, since the environmental conditions of our lab are well-controlled and the contrast in two-beam interferometers is a forgiving function of the ratio of intensities in the contributing arms.

A small portion of the light transmitted through the modulator is diverted via a 99:1 fiber tap to use as a safety interlock for the 1550 nm laser amplifier, preventing unseeded operation. The modulated seed light after insertion losses and losses at the modulator is typically \( \approx 3 \) mW, which is sufficient to drive the amplifier into saturation, fully compensating transmission losses. The amplified, modulated light is spatially overlapped in free space with a pure tone from a 1050 nm fiber laser. Both beams are then mixed inside a \( \approx 43 \) GHz-bandwidth SFG stage with quasi-phase matching. The temperature of the SFG stage is stabilized around 180 °C to offset photorefractive damage, with a precision of \( \pm 0.01 \) °C via a commercial oven controller (Covesion Ltd. PV40 oven with OC1 controller).

The SFG stage produces two equal-strength tones at \( \approx 626 \) nm, with total power \( \approx 1 \) W. The two spectral components are then split at the Mach-Zehnder beamsplitter, and each of the outputs is sent to individual resonantly-enhanced SHG stages to double to \( \approx 313 \) nm for EIT cooling. The doubling process also doubles the frequency-spacing between the sidebands from \( \approx 27.5 \) GHz to \( \approx 55 \) GHz, as required by the application.

IV. BEAMSPFITTER PERFORMANCE

We characterize the MZ-BS with regards to its ability to successfully separate the two spectral tones, performance stability over time, and overall power efficiency. We quantify the splitting efficiency by the achieved interferometric contrast \( C \) through the interferometer. Low contrast means incomplete splitting, which directly translates to loss of power in the desired spectral component per arm. The contrast can be defined as

\[
C = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = \frac{2\sqrt{I_1I_2}}{I_1 + I_2},
\]

where \( I_{\text{max/min}} \) are the maximum/minimum signal intensity as measured on a detector at the output port. Here, \( I_{1,2} \) are the intensities of light in each of the two interfering arms reaching the same port, assuming monochromatic light of identical polarization. Measurements presented are for s-polarized input light, optimized for the passive optical elements in use. The predicted and measured contrast for s-polarized light assuming identical performance in both cubes is shown in Tab. II.

When the interferometer’s length is stabilized we may measure the spectrum of the output light using a pair of Fabry-Perot interferometers (SA200-5B) aligned to each of the output ports, as shown in Fig. 4a. We characterize the stability of the interferometer by measuring the ratio of the transmitted and rejected sidebands for each output port, and then calculating the modified Allan deviation of this ratio as a function of averaging time \( \tau \) (Fig. 4b). We elect to use this measure
The combined multi-tone infrared light passes a sum frequency generation (SFG) stage where both tones are converted to visible light. The Mach-Zehnder beamsplitter spatially separates the tones into two arms with near single-tone spectra, which are delivered to second harmonic generation (SHG) stages. Inset boxes show spectral intensity $I$ as a function of frequency $\omega$, SFG conversion efficiency indicated in purple.

TABLE I. Interferometer contrasts predicted from component specifications, and direct measurements, where the large theoretical errors stem from the wide component performance tolerance in the cubes.

| Port | $C_{\text{theory}}$ (%) | $C_{\text{measured}}$ (%) |
|------|--------------------------|---------------------------|
| 1'   | (97.5 ± 2.0) %           | (98 ± 1) %                |
| 2'   | (99.9 ± 2.0) %           | (98 ± 1) %                |

over the more common (overlapping) Allan deviation because it can distinguish between flicker- and white-phase noise averaging through the power-law scaling in $\tau$, while the other two can not. The $\tau^{-3/2}$ scaling indicates an underlying flicker-phase noise fluctuation in the ratio. Overall, bulk transmission through the device is measured at 81% limited by the cube and prism absorption of \( \approx 6\% \) each; this number can be easily improved by using lower-absorption components. Observed performance depends on input polarization state mainly due to performance variation in the beamsplitter coatings.

V. CONCLUSION

In this work we presented and characterized a Mach-Zehnder beamsplitter to separate two closely spaced spectral components imposed on a single beam. With our choice of optics we found that $> 98\%$ of the power in each spectral component exits on the correct port, and that fluctuations in the splitting ratio of the actively length-stabilized assembly scale in time like a flicker-phase-noise model for measurements up to 10 min. This phase noise is likely introduced within the electronics of the feedback chain, and may pose a limitation if long-timescale stability in the intensity or spectral purity is required. In our application, spectral purity is guaranteed by the resonance condition of the SHG units, and low frequency intensity fluctuations are easily removed by downstream intensity stabilization. In our implementation both interferometer footprint and transmission performance are limited by design choices optimizing convenience and cost, and can be improved by utilizing more specialized components and assemblies.

In our atomic-physics application, the setup described here saves considerably in cost and overhead compared with producing two beams from separate nonlinear frequency conversion and phase-locked source lasers. This is because it requires no GHz-scale detection or lock electronics, and only employs a single laser source. Power- and cost-efficient generation of two tones from a single source is available as turn-key solutions from near DC to sideband separations of $\Delta \nu \approx 50\,\text{GHz}$ prior to SFG by utilizing commercial telecommunications-band waveguide intensity modulators prior to a saturated amplifier and double-sideband suppressed-carrier amplitude modulation. At increasingly...
large frequency splittings other considerations like the conversion bandwidth of the nonlinear medium for SFG are likely to become limiting factors in available power, rather than the MZ-BS. Two-tone light may be physically split by the Mach-Zehnder beamsplitter at any power and carrier frequency for which suitable optics are available. In the future we will use this system to generate the required phase-coherent beams for EIT cooling of a 2D crystal beryllium ions in a Penning trap close to their motional groundstate. We are hopeful that the simplifications and cost-reductions afforded by this stable MZ-BS system will prove useful in a variety of atomic and optical physics experiments, where spatially splitting or combining laser beams with closely spaced frequencies is required.

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