Lossless beam combiners for nearly equal laser frequencies

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We discuss three ways to combine two laser beams with equal linear polarizations and very closely spaced frequencies into a single output beam containing up to 100% of the input power of each beam. One setup, a modified Mach–Zehnder interferometer, is examined in detail; it allows to adjust the combined output power electronically with the help of a simple servo loop. With off-the-shelf optical components we obtained a 98% efficiency. © *2000 American Institute of Physics.* [S0034-6748(00)03802-8]

I. INTRODUCTION

Laser cooling and trapping of alkali atoms has become a common tool and area of study in modern atomic physics and spectroscopy. In general it requires two superposed laser beams with equal polarizations but slightly different frequencies. For example, in cesium the two lasers have to be tuned close to the cooling transition $6^2S_{1/2}$, $F=4 \mapsto 6^2P_{3/2}$, $F=5$ and to the repumping transition $6^2S_{1/2}$, $F=3 \mapsto 6^2P_{3/2}$, $F=4$, amounting to a frequency separation of 8942 MHz. Usually the two laser beams with parallel linear polarizations are superposed on a beamsplitter and then traverse a quarter-wave plate before interacting with the atoms. However, half of the total incident laser power is lost through the unused output port of the beam splitter, even when an asymmetric splitter (no 50:50 splitting ratio) is used to preferentially retain more of one laser beam's power at the expense of the second. Of course it would be preferable to have the full input power available because oftentimes the performance of the overall system (e.g., the total flux of laser-cooled atoms) increases with increasing saturation of the atomic transitions.

There are various techniques that allow to superpose two beams of different frequency but identical polarization. When the wavelength difference is large enough (several 10 nm) a dichroic mirror reflecting one wavelength and transmitting the other is most straightforward [Fig. 1(a)]. For more closely spaced wavelengths the two beams can be sent through a diffraction grating or a prism at suitably different angles of incidence, such that they emerge after diffraction/refraction exactly superposed [Figs. 1(b) and 1(c)]. However, for the small frequency separations of only a few gigahertz required for the laser cooling experiments these methods cannot be employed for principal or practical reasons.

We should note that a small nonzero frequency difference between the beams to be superposed constitutes the most difficult case: if the frequencies are equal it is possible to electronically phase lock the laser sources onto each other such that they can be combined on a normal beam splitter without losses to the second output port, as has been studied in the context of phase-array laser ranging[1] and of telecommunications.[2] Alternatively, a waveguide electro-optic beam combiner can be used.[3]

Here we present three setups that allow to combine 100% of the power of two laser beams with very nearly equal frequencies. One of the methods is examined and characterized in detail. All three setups rely on frequency selective interference effects and are therefore applicable to any desired difference frequency, unlike the clever trick used by Gruneisen *et al.* to combine two laser beams using the optical nonlinearity of a potassium vapor.[4]

II. THREE WAYS TO COMBINE BEAMS WITHOUT LOSSES

A. Faraday isolator

In Fig. 2(a) the Fabry–Pérot resonator is tuned on resonance for laser frequency 1 while being far off resonant for laser frequency 2 so that beam 1 is transmitted completely while beam 2 is reflected. After interaction with the resonator both beams are coupled out of the reverse exit of the Faraday isolator. It can act here as an optical diode for both laser frequencies simultaneously because they are so similar that dispersion in the Faraday rotator material does not yet play a role.

This setup has two disadvantages. Not only is a Faraday isolator perhaps the most expensive piece of equipment in the whole setup but also has the resonator to be stabilized to laser frequency 1 extremely well in order to avoid amplitude or phase fluctuations of the output beams.

An advantage of this setup is that it can be cascaded in order to combine more than two beams. The combined first two beams take the role of beam 2 in Fig. 2(a) while a third beam is added with the help of an additional resonator with whom it is resonant while beams 1 and 2 are not, etc.

B. Polarizing beamsplitter

A very similar setup is shown in Fig. 2(b) where the only difference to Fig. 2(a) is the replacement of the Faraday isolator by the combination of a quarter-wave plate and a polarizing beam splitter. Satisfactory performance requires that the resonator does not distort the incident circular polarization state. This requirement might be hard to meet because a resonator built from discrete components usually exhibits a small birefringence, a fact which is sometimes exploited for laser stabilization.[5]

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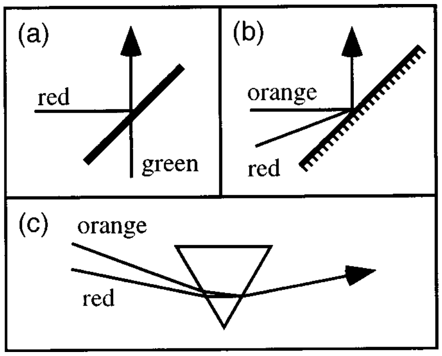

FIG. 1. Several ways to combine two independent laser beams. (a) Dichroic mirror; (b) diffraction grating; and (c) prism.

C. Mach–Zehnder interferometer

1. Principle of operation

The frequency selective element can also be of the Mach–Zehnder type [Fig. 3(a)]. Each laser beam enters through one of the two input ports of the two-beam interferometer. The length of path B is chosen such that path A and path B lead to completely constructive interference at output port 1 for both beams. In effect, both laser beams emerge at the same output port with ideally all their input power while no light comes out of the other output port. Which one is the bright and which one the dark output port depends on the overall phase difference accumulated along paths A and B and by changing it over the range of half a wavelength the splitting ratio of 100:0 can continuously be tuned all the way to 0:100.

With the geometrical quantities defined in Fig. 3(a) the optical path difference along paths A and B is

$$\Delta r = 2f + nb - e, \tag{1}$$

where n is the index of refraction of the prism with base-length b. The phase shift of each of the two laser beams at output port 1 is given by $\delta_1 = k_1 \Delta r$ and $\delta_2 = k_2 \Delta r + \pi$ where the 180° phase shifts upon reflection at a beam splitter have been taken into account.

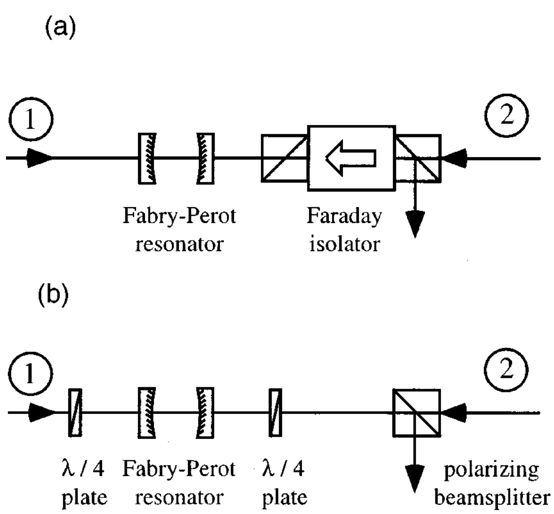

FIG. 2. Two lossless beam combiners for two independent laser beams of nearly equal frequencies using a Fabry–Pèrot resonator as frequency-selective element.

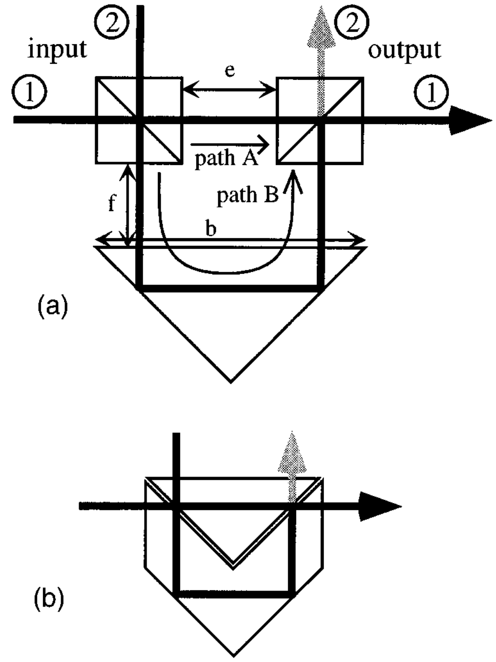

FIG. 3. Lossless beam combiner based on a modified Mach–Zehnder interferometer. (a) Notation used in the text; and (b) optimized compact setup.

Operation as a lossless beam combiner requires an interference maximum for both beams at port 1 so that $\delta_1 = N_1 \cdot 2\pi$ and $\delta_2 = N_2 \cdot 2\pi$ with integer N_1 and N_2. With $\delta_2 - \delta_1 = (k_2 - k_1)\Delta r + \pi = \Delta k \Delta r + \pi$ and $\Delta k = 2\pi \Delta \nu / c$ one obtains

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

and with (1):

$$f = \frac{1}{2}\left[\left(N_2 - N_1 - \frac{1}{2}\right)\frac{c}{\Delta \nu} - nb + e\right]. \tag{3}$$

For $n = 1.5$, $b = 28$ mm and $\Delta \nu = 8942$ MHz for cesium the beam combiner works for a series of values of f separated by $c/2\Delta \nu = 16.8$ mm.

However, f only has to be tuned to the correct length relative to this length scale. This means that for any of the interference maxima for beam 1 near the ideal f the pattern for beam 2 will also be very close to its maximum. In practice, therefore, it is only necessary to mechanically set f to any interference maximum near one of the ideal positions to within a millimeter or so. Fine tuning can then be done with the help of a piezoelement moving the prism. Choosing f further away from the optimum amounts to a change in the power balance, i.e., the relative transmitted powers of beams 1 and 2.

A practical advantage of this setup is that the signal at the other output port can be used as an error signal for an electronic stabilization of f and therefore the power ratio between both output ports. And of course the setup also works in reverse, i.e., as a beam splitter that perfectly separates two laser beams of identical polarizations and closely spaced frequency. In addition, the separation of frequency modulation sidebands from the carrier is possible with this setup.

TABLE I. Numerical values for the reflectivity and transmittivity of the optical components for *s* and *p* polarizations.

Quantity	Cube 1	Cube 2	Prism
R_s	54.3%	53.9%	78.0%
R_p	48.4%	49.7%	93.9%
T_s	29.5%	29.2%	
T_p	39.6%	39.5%	

2. Experimental realization

For the experimental demonstration of the lossless beam combiner the available optics was not quite ideal (see Table I). In particular, the beamsplitter cubes were slightly lossy (partly due to reflections from the cube faces) and had an asymmetric splitting ratio.

If P_{ij} is the power of laser beam 1 arriving at output port *i* via path *j* the contrast of the interference pattern obtained by a variation of *f* is

$$C_{i,\alpha}=\frac{2\sqrt{P_{i\mathrm{A}}P_{i\mathrm{B}}}}{P_{i\mathrm{A}}+P_{i\mathrm{B}}}, \tag{4}$$

where α is ''*s*'' or ''*p*,'' depending on the direction of the linear input polarizations with respect to the beamsplitters. For instance, one expects from the measured values given in the table that for beam 1 $C_{1,s}=89.2\%$, $C_{2,s}=99.2\%$, $C_{1,p}=98.6\%$, and $C_{2,p}>99.9\%$ and very similar values for beam 2. Due to the imperfect characteristics of the available components the performance of the interferometer should be slightly better for *p* polarization than for *s* polarization.

While the most compact setup is obtained for $e=0$ and for $N_2-N_1=2$ ($f=4$ mm) a more convenient separation of $f=21$ mm ($N_2-N_1=3$) was chosen. Furthermore, the prism was mounted on a piezoelement, thus allowing scanning and fine adjustment of *f*.

3. Results and practical considerations

By varying the piezovoltage the fringes of the interference pattern at port 1 were observed and their contrast was found as $C_{1,s}=75\%$, $C_{2,s}=96\%$, $C_{1,p}=91\%$, and $C_{2,p}=96\%$ (see Fig. 4 for an example), proving that the device works as expected. A contrast of 96% means that 98% of the input power of each beam emerges from the desired output port. Since the setup constitutes a two-beam interferometer its fringe width is relatively broad so that it is easy to lock the interferometer to its operating point with a simple servo loop even in a noisy environment. The error signal for the ideal beam combiner is derived from the ''dark'' output port 2 by choosing a value of *f* such that a few percent of the light come out that way. It is therefore possible to electronically switch the output power of the beam combiner by adding an electronic offset to the error signal.

In order to reduce the sensitivity of the beam combiner to external influences like acoustics or thermal drift, and in order to reduce its losses due to reflections from glass surfaces, one can employ a compact arrangement [Fig. 3(b)] consisting of a chevron-shaped prism and a rectangular prism where the interface between the two is coated for 50% reflection and 50% transmission. For practical reasons one would not choose a completely monolithic setup but allow for in-and-out shifting of the two prisms with respect to each other [this is equivalent to a change of *f* in the discrete setup of Fig. 3(a)].

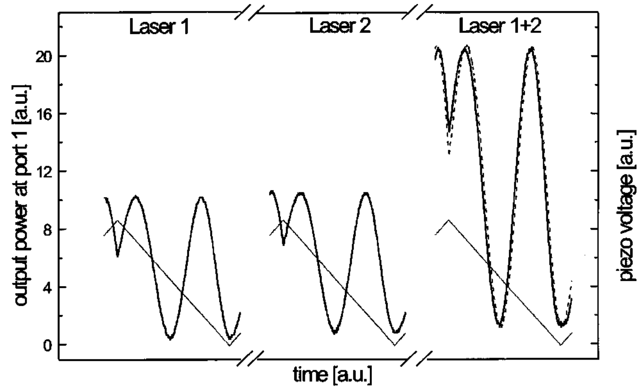

FIG. 4. Measured power at one output port as a function of path length in the interferometer: (a) laser 1 only, (b) laser 2 only, and (c) both lasers unblocked (solid curve). For comparison the numerical sum of traces (a) and (b) is also shown (dashed curve).

III. APPLICATIONS

The setups described here allow to superpose two laser beams of equal linear polarizations and of nearly equal frequency with the total input power of both beams transmitted to the output. Particularly the arrangement shown in Fig. 3 could have practical applications, for instance in laser cooling, because of its experimental simplicity and robustness.

Two other applications rely on the effect of the Mach–Zehnder arrangement on a comb of equally spaced light frequencies. When the mode spacing matches the characteristic frequency $\Delta\nu$ of the lossless beam splitter all even-numbered modes emerge from one output port while all odd numbered come out the other port. Such a comb of frequencies is characteristic of the output of a mode-locked laser, where these modes are coherently coupled, resulting in a train of pulses with a repetition rate equal to the mode spacing $\Delta\nu$. If the input light to our device is provided by such a laser each output beam has twice the repetition rate, because now the mode spacing is $2\Delta\nu$. In a wavelength-division multiplexed telecommunication scheme the spacing between adjacent channels is twice as high at the output as compared to its input. Successive stages of lossless beam splitting lead to higher and higher channel separation, making the complete demultiplexing by conventional means easier. One can envision much higher data transfer rates on existing lines because of the denser distribution of channels.

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