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Low-cost setup for generation of 3 GHz frequency difference phase-locked laser light

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We have devised an all-optical setup for the generation of two phase-locked laser fields with a frequency difference of 3 GHz using only standard optics and two acousto-optical frequency shifters, that are operated at 253 MHz in sixtupel pass. The spectral width of the beat frequency is measured to be 300 Hz (full width at half maximum) limited by the resolution bandwidth of the spectrum analyzer. We routinely obtain an overall efficiency of more than 15% and demonstrate that the frequency shifted light can be further amplified by injecting it into additional ''slave'' lasers. This setup provides a low-cost alternative over conventional methods to generate laser fields with difference frequencies in the GHz domain, as for example, used in laser spectroscopy, laser cooling and trapping, and coherent manipulation of atomic quantum states. © *2000 American Institute of Physics.* [S0034-6748(00)03109-9]

I. INTRODUCTION

Laser sources with a fixed frequency difference are widely used in areas such as laser spectroscopy,[1] manipulation of atomic and molecular states,[2] or laser cooling and trapping.[3] Some applications, for example coherent control of internal quantum states, Raman cooling of atoms, quantum information processing with atoms and ions, or various configurations in atom interferometry require two or more laser fields with difference frequencies of several GHz that are phase locked or at least have no fluctuations in the frequency difference which are larger than 1 kHz.[4] There are a number of techniques used to obtain laser fields with such a frequency difference, e.g., high frequency acousto-optical frequency shifters (AOMs)[5] or electro-optical modulators (EOMs),[6] phase locking with an electronic servo loop,[7] or locking to different longitudinal modes of a tunable Fabry–Perot resonator.[8]

For diode lasers, there is also the option of directly modulating the laser diode injection current.[9] We present a simple method to obtain frequency differences of a few GHz, that is solely based on standard low frequency acousto-optical components, thus providing a low-cost alternative to the previously mentioned methods that all require some sort of expensive high frequency component.

II. EXPERIMENTAL SETUP

In our setup we generate two phase-locked laser fields with a frequency difference of 3.036 GHz (corresponding to the hyperfine splitting of the ground state of the rubidium isotope ^{85}Rb) by splitting an incoming light field into two beams that are both frequency shifted by 1.518 GHz with an opposite sign. In each leg, this frequency shift is obtained by using an acousto-optic frequency shifter that is operated in three successive double passes at 253 MHz. This is achieved by ensuring that the three pairs of light beams which correspond to the three double passes traverse the AOM under slightly different angles. After recollimation, the output beams of the double passes have a relative displacement that is sufficiently large so that they can be separated from each other.

Figure 1 shows the optical configuration of one of the two legs of our setup. After passing through a polarizing beamsplitter (PBS) the input beam is focused into an AOM (Crystal Technology Inc., Model 3200, center frequency 200 MHz, operated at 253 MHz). At this frequency, single pass diffraction efficiencies of 82% into the first order can still be achieved. The light diffracted into the first order is reflected and focused back into the AOM by a curved mirror. That part of the retroreflected light that is diffracted into the first order during the second pass is recollimated by the initial focusing lens and is counterpropagating along the path of the incoming beam. Due to the double pass through a quarter-wave plate ($\lambda/4$) between AOM and retroreflecting mirror its polarization is rotated by 90° so that it can be separated from the incoming beam at the PBS. With two mirrors and a lens, the beam is then vertically displaced by 2–3 mm [see side view of (a) in Fig. 1] and redirected into the AOM for the third and the fourth pass. Due to the vertical displacement the beam crosses the AOM under a slightly different angle [side view of (a) in Fig. 1]. The additional action of the quarter-wave plate ensures that the light after the fourth pass is transmitted by the polarizing beamsplitter. Due to the different beam height it can be separated from the incoming beam by a sharp-edged mirror. The beam is again vertically displaced and sent back into the AOM for the fifth and the sixth pass, before it is extracted from the setup by a second sharp-edged mirror [see side view of (a) in Fig. 1].

With this setup we obtain maximum overall diffraction efficiencies of 24% for a total frequency shift of 1.518 GHz. With only minor daily adjustments, we routinely obtain an overall efficiency of more than 15% on a day to day basis, the efficiency for the first four passes being more than 75% per pass and the efficiency for the fifth and sixth pass being slightly less (about 70%). This reduction in efficiency is probably due to the fact, that the total vertical displacement

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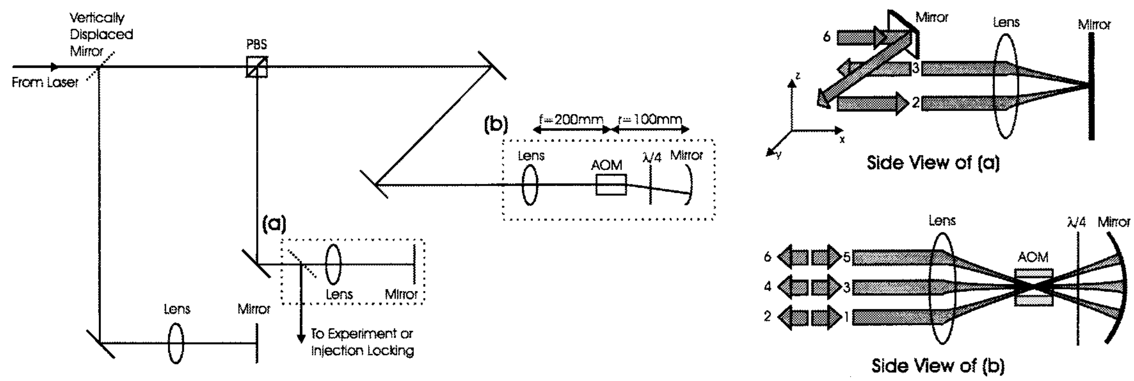

FIG. 1. Optical configuration for frequency shifting of a laser field by 1.518 GHz using a single low frequency acousto-optic frequency shifter (AOM). The AOM is operated at 253 MHz in sixtupel pass (i.e., three double passes). We have obtained an overall efficiency of up to 24%.

is too large to obtain maximum efficiency for the last two passes. An identical setup is used for the second leg with the light being diffracted into the minus first order for all passes. Thus, two phase-locked laser beams with a frequency difference of 3.036 GHz are generated.

This multiple pass frequency shifter can be applied to all typical cw laser sources. In our case, the input beam is generated by a diode laser system at 780 nm. The complete setup is depicted in Fig. 2. It consists of an extended cavity diode laser (Master) whose output is injected into a free running diode laser (Slave 1) giving an output power of 40 mW. The output of this slave laser is split into two beams of 20 mW which serve as the input beams for the sixtupel frequency shifters. With an overall efficiency of 15% each frequency shifted beam has about 3 mW of laser light, which in many cases is sufficient for the experiment. For additional laser power we use this light for injection locking of additional slave lasers (Slaves 2 and 3), thus generating two phase-locked laser beams with a frequency difference of 3.036 GHz, each having a power of 40 mW. If required, the master laser can also be stabilized to an atomic resonance using saturation absorption spectroscopy or another technique.

III. BEAT MEASUREMENTS

In order to characterize the laser system we have performed a beat measurement of the output light of the final slave lasers (Slaves 2 and 3), each at a power of 40 mW (Fig. 3). The two AOMs were driven by the amplified rf output of a common radio-frequency synthesizer.[10] The output light of the diode lasers is combined on a beamsplitter and sent onto a fast photodetector (New Focus Model 1437). The amplified detection signal is analyzed with a rf spectrum analyzer. The measured linewidth of the beat signal of 300 Hz full width at half maximum (FWHM) is limited by the resolution bandwidth of the spectrum analyzer (300 Hz). The maximum of the signal is at least 43 dB above the noise level. No sidebands above the noise level can be observed (see also Fig. 4). The drift of the difference frequency is given by the drift of the output frequency of the rf source multiplied by the total number of passes through both AOMs (12 in our setup) giving a drift of a few Hz per day for a standard rf synthesizer.

As shown in Fig. 4, with this setup optimized for a frequency difference of 3.036 GHz we can cover the range of frequency differences from 2.51 to 3.17 GHz simply by adjusting the output frequency of the rf source driving the AOMs. Over the entire tuning range, the strength of possible sidebands is at least 40 dB below the signal strength. No adjustments of the optical alignment have been necessary to achieve this tuning range. For each sixtupel frequency shifter this results in a tuning range of at least 300 MHz and a maximum frequency offset of more than 1.5 GHz using only a single 200 MHz AOM. The tuning range can even be further extended by readjusting the alignment of the two frequency shifted beams injected into the two slave lasers (Slaves 2 and 3).

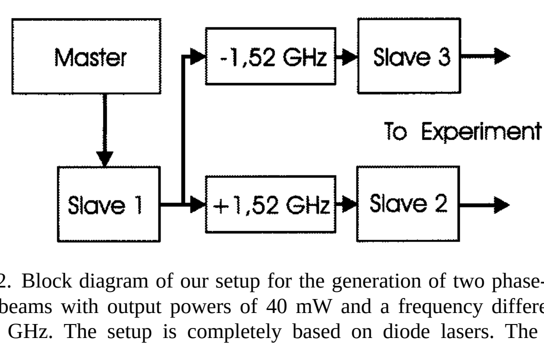

FIG. 2. Block diagram of our setup for the generation of two phase-locked laser beams with output powers of 40 mW and a frequency difference of 3.036 GHz. The setup is completely based on diode lasers. The blocks labeled ‘‘±1.52 GHz’’ contain the setup of Fig. 1.

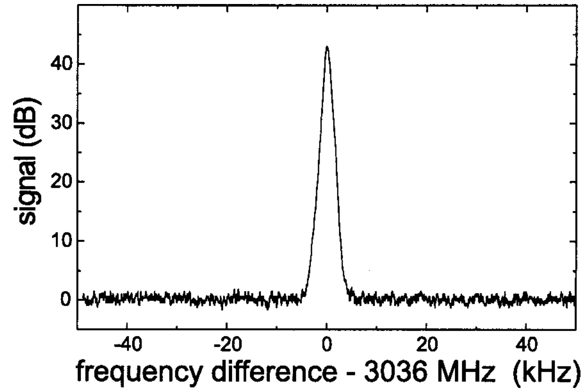

FIG. 3. Beat measurement of the output light of Slaves 2 and 3 of Fig. 2. The measured linewidth (FWHM) of 300 Hz is limited by the resolution bandwidth of the spectrum analyzer (300 Hz).

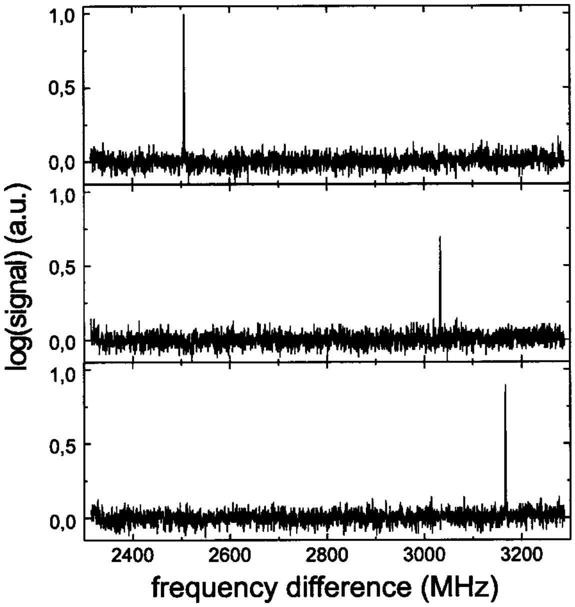

FIG. 4. Beat measurements of the output light of Slaves 2 and 3 of Fig. 2 for three different values of the rf frequency driving the AOMs. The measured beat frequencies are 2.508, 3.036, and 3.168 GHz. The measurement shows the large scan range and the absence of sidebands above the noise level.

IV. DISCUSSION

The setup presented here with its comparatively high efficiency and its large frequency scan range provides an attractive alternative to other methods to generate phase-locked laser light with frequency differences in the GHz range. This is also due to its many inherent advantages. First, it uses only standard low frequency components, thus discarding the high frequency components that are normally used for this purpose, such as high frequency rf sources, high frequency detectors, or high frequency AOMs or EOMs. A further advantage lies in the fact, that with only minor adjustments in the optical setup (e.g., altering the number of passes through the AOMs) our system can deliver all frequency differences from 0 to 3.2 GHz without the need to buy a set of AOMs or EOMs at various center frequencies. Compared to the usage of an EOM or the direct modulation of the laser diode injection current, additional carriers or sidebands, which are unfavorable for many applications such as injection locking, are absent. An additional advantage lies in the fact that only one master laser is needed, compared to the two master lasers that are required in the case of phase locking using electronic servoloops.[7] Also, since there are no electronic locking circuits, the quality of the phase lock is not limited by the bandwidth of the servoloop.

Due to its compactness and low cost, this setup will be attractive for a number of areas in laser science. Possible applications in the field of atomic physics and quantum optics include the generation of coherent superposition states (via two photon Raman transitions) for atom interferometry, quantum computing, and more generally quantum engineering. The required frequency differences for the generation of coherent superposition states of the hyperfine ground states of the frequently used alkaline atoms range from 228 MHz for ^{6}Li to 9.2 GHz for ^{133}Cs. The frequency differences for ^{6}Li (228 MHz), ^{7}Li (804 MHz), ^{23}Na (1.772 GHz), ^{39}K (462 MHz), ^{40}K (1.286 GHz), ^{41}K (254 MHz), and ^{85}Rb (3.036 GHz) are easily achievable as demonstrated in this article. While frequency differences above 3 GHz are in principle still available by cascading our scheme to more than six passes, the 6.835 GHz for ^{87}Rb and 9.192 GHz for ^{133}Cs probably require an additional set of slave lasers and AOMs. Our setup is also well suited for a large variety of laser cooling methods, such as Raman cooling, where laser fields with fixed or even phase-locked frequency differences are necessary, but also for Doppler cooling in cases where an additional repumping laser is normally needed.

ACKNOWLEDGMENTS

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[10] In our setup, no narrow-bandwidth rf source (such as a synthesizer) is required to produce the phase-locked laser light. It is only needed when the frequency difference has to be stable in addition.