Generation of high-power laser light with Gigahertz splitting

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We demonstrate the generation of two high-power laser beams whose frequencies are separated by the ground state hyperfine transition frequency in ^{87}Rb. The system uses a single master diode laser appropriately shifted by high frequency acousto-optic modulators and amplified by semiconductor tapered amplifiers. This produces two 1 W laser beams with a frequency spacing of 6.834 GHz and a relative frequency stability of 1 Hz. We discuss possible applications of this apparatus, including electromagnetically induced transparencylike effects and ultrafast qubit rotations. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2776971]

I. INTRODUCTION

The hyperfine ground states of alkali-metal atoms are among the most commonly utilized in atomic physics experiments. Traditionally, these states have been used in atomic clocks that are accurate at the 10^{-15} level.[1] When isolated from the environment, these states have extremely long decoherence times and therefore are ideal candidates for storing quantum information.[2–5] Hyperfine states have also been used extensively in many studies of quantum interference phenomenon including electromagnetically induced transparency (EIT),[6,7] slow light,[8,9] stopped light,[10,11] and enhanced refractive index.[12,13] Recently, optical spatial soliton formation that utilize hyperfine transitions in a vapor cell of alkali atoms has also been suggested.[14]

The transitions between two hyperfine states are dipole forbidden. As a result, these transitions are accessed by two laser beams whose frequency difference equals the transition frequency in a two-photon Raman configuration. For many experiments mentioned above, the amount of available optical power for these transitions is critical. In quantum computing, the optical power determines the speed of single-qubit gates between hyperfine qubit states.[4,5] For refractive index enhancement, the optical power determines the maximum value of the index that can be achieved.[13] Spatial solitons formed in alkali vapor cells also require substantial power to allow for sufficiently large detuning from the excited state to reduce dissipation.[14] The alkali metals feature ground state hyperfine transition frequencies in the gigahertz range [^{87}Rb (6.834 GHz), ^{85}Rb (3.035 GHz), ^{23}Na (1.772 GHz), and ^{133}Cs (9.193 GHz)]. Therefore, an experimental design that can produce a stable source of laser light precisely offset by several gigahertz and having high levels of available optical power is of particular interest to the atomic physics community.

In this letter, we experimentally demonstrate a system that achieves an order of magnitude more optical power with gigahertz splitting when compared with previous approaches. Specifically, we produce two 1 W laser beams with a frequency spacing of 6.834 GHz which is the hyperfine transition frequency in ^{87}Rb. The relative frequency stability between the two lasers is at the hertz level. Noting Fig. 1, we utilize a configuration of high frequency acousto-optic modulators (AOMs) and semiconductor tapered amplifiers. We start with a master oscillator, an external cavity diode laser, whose frequency can be precisely tuned and locked via saturated absorption spectroscopy. The output beam of the master oscillator is coupled into a semiconductor tapered amplifier which generates optical power in excess of 1 W at the master frequency. This light is then divided between two high frequency AOMs which shift the relative frequencies by 6.834 GHz. The diffracted orders are then coupled into two additional tapered amplifiers. In addition to an order of magnitude power increase, this system has the added benefit of requiring no additional locking mechanisms such as a phased locked loop (PLL) based approach.

Before proceeding with a detailed description of our scheme, we would like to summarize existing experimental designs for generating laser light with gigahertz frequency separations. Microwave modulation of the laser current[4,5,15] and electro-optic modulation[16,17] put sidebands on the laser and filter out the center frequency with a cavity. The PLL approach synchronizes the output of a low noise local oscillator laser and an inexpensive diode laser.[18,19] Previously, low frequency AOMs have been used to achieve gigahertz shifts in a sextuple pass configuration.[20] Optical powers of up to 40 mW have been achieved by seeding the shifted output beams of the above processes into a diode laser in a slave configuration.[15,20] Alternatively, several Ti:sapphire based PLL designs have several hundred milliwatts of power in the local oscillator beam, but low power in the phase locked beam.[18,19]

II. COMPONENT DESIGN AND PERFORMANCE

A. Master oscillator

The design of our external cavity diode laser (ECDL) closely follows the design of Arnold *et al.*[21] with modifications by Hawthorn *et al.*[22] We use a Sharp laser diode (GH0781JA2C) which provides high output power and low cost but sacrifices tunability. Temperature and current control are provided via commercial Newport 325B and 505B drivers. An extensive review of this design can be found in pre-

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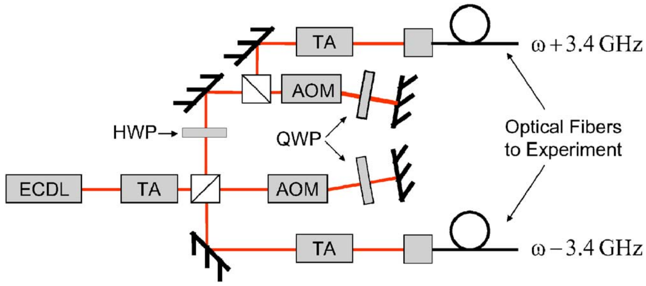

FIG. 1. (Color online) Block diagram of the apparatus. Light generated by a single MO is amplified by a TA up to 1 W of optical power. This light is divided between two AOMs that shift the laser frequencies by a total of 6.834 GHz and have a diffraction efficiency of 1.3%. The shifted beams are then reamplified by two additional TAs, giving 1 W of optical power in each frequency component. This light is then coupled into a single mode fiber. Abbreviations: master oscillator (MO), tapered amplifier (TA), acousto-optic modulator (AOM), quarter wave plate (QWP), and half wave plate (HWP).

vious publications.[21–23] Here, we report a mode hop-free tuning of 5 GHz, a submegahertz linewidth, and an output power of 50 mW at 105 mA of operating current. We find this design to be exceptionally stable over months of operation, as it has maintained its absolute frequency with no mechanical adjustments.

B. Tapered amplifiers

Our optical system employs three identical tapered amplifiers (TAs). The TAs are based on Eagleyard semiconductor devices (EYP-TPA-0780-01000). The housing is based on the design of Nyman *et al.*[23] with modifications made to the lens handling system and the base plate. The amplifier chip is positioned in a three piece oxygen-free high conductivity (OFHC) copper block assembly which acts as the TA anode connection and provides structural stability and thermal dissipation. The copper blocks are threaded to accept custom designed lens mounts which allow positioning of the collimating optics to a few microns precision. This amplifier housing is mounted on a thermoelectric cooler (TEC) which is in turn mounted on an aluminum base. The base houses the electrical connections, provides mechanical stability, and raises the output beam to the required height. A Plexiglas enclosure fitted with optical windows isolates the amplifier from the environment, protecting the chip from dust and humidity.[24] We find the mechanical stability of this design to be excellent, requiring minimal realignment over several months of use.

The diode current and temperature stabilization are provided by off the shelf drivers (Newport 325B and 525B). The temperature is proportional-integral-derivative (PID) feedback stabilized with a monitor thermistor positioned as close to the amplifier chip as possible. We find that the heat generated by the amplifier does not exceed 3 W and can be handled with a single TEC and no water cooling, provided that the system is in good thermal contact with the base and table.

Performance of tapered amplifiers has been covered in great detail in the literature.[23,25,26] We note that the devices are strongly dependent on the polarization of the seeding light and recommend positioning a half wave plate immedi-

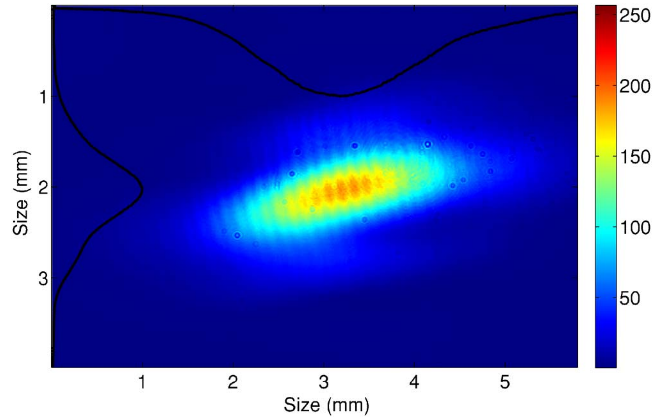

FIG. 2. (Color online) Intensity of the TA output beam after correction with a single cylindrical lens and a 2:1 telescope. Line profiles of the average intensity in the X and Y directions are superimposed, showing nearly Gaussian shape. Greater than 600 mW of this 1 W beam can be coupled into a single mode fiber. The striped pattern is a result of interference on the profiling charge coupled device (CCD), and the small speckles are dust particles.

ately upstream to maximize the output. We report that given careful alignment, 2 mW of seeding light is sufficient to attain 1.0 W of output, +27 dB gain. Of this, 80 mW is broadband amplified spontaneous emission (ASE). Even after subtracting the ASE, our recorded gain greatly exceeds the +13 dB of gain specified by the manufacturer. Beam shaping of the output is accomplished using a single 50 mm cylindrical lens positioned after a collimating lens. This gives a 3:2 mm elliptical beam. The input power is well below the saturation limit for these devices, so no top hat structure is seen in the output (Fig. 2). After the cylindrical lens, the beam is passed through an optical isolator. We find that the amplifiers are very sensitive to back reflections as the waveguide structure at the input facet is very fragile. With mode matching, greater than 60% of the amplified light can be coupled into a single mode, polarization maintaining fiber.

C. Frequency shifters

Once the master oscillator beam is amplified, it is then split into two beams which are sent to the frequency shifters (Fig. 1). If desired, a third beam of unshifted light can be split out and fiber coupled for use in experiments which require an additional beam.[13]

The required frequency shift, 6.834 GHz, is accomplished by shifting each of the two beams with high speed AOMs. These devices have a center frequency of 1.7 GHz, a bandwidth of 150 MHz, and high power optical coatings (Brimrose TEF-1700-150-780). The AOMs work in a parallel, double passed, configuration. One beam is shifted up 3.4 GHz using the positive first order and the other beam is shifted down 3.4 GHz using the negative first order. The 1 W of input rf for each AOM are provided by independently operating HP 8673D function generators supported by Miteq AMF series amplifiers.

At each AOM, the input beam is focused down to a 60 μm waist with a 125 mm lens. Alignment into the AOM crystal is controlled with a five axis translation stage and optimized by maximizing the diffracted power. The dif-

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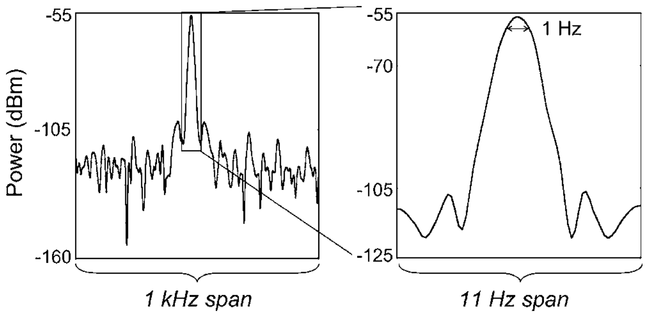

FIG. 3. Beam beating experiment. The two output beams from the apparatus are combined via a beam cube and polarizer. The resultant beam is then incident on a high speed photodiode, through an optical fiber. The displayed center frequency is 6.834 GHz, mixed down to 30 MHz. The span in the main image is 1 kHz, while the inset span is 11 Hz. The measured FWHM of the center peak in the inset is 1 Hz and is limited by the instrument resolution.

fracted beam then passes through a collimating lens and a quarter wave plate before being retroreflected back into the crystal. The final, doubly shifted beam is separated from the input via a polarizing beam cube. It should be noted that, given the large Bragg angle associated with the high frequency of these devices, a portion of the beam will reflect off the transducer. Care must be taken during alignment to disentangle this unshifted portion from the shifted light. A series of razor blades reduces this contamination to below 0.1% of the final amplified beam.

Low diffraction efficiency of the frequency shifter is the primary motivation for initially amplifying the master oscillator (MO). We achieve maximum single pass efficiencies of 13% with the polarization parallel to the transducer. When the polarization is perpendicular to the transducer, the maximum attained efficiency drops to 10%. In a double pass configuration, this implies a total efficiency of 1.3%. Thus, supplying 200 mW of optical power to each AOM provides enough light to sufficiently seed the TA.

This system is designed to be flexible. For example, if we wish to attain the required frequency splitting for ^{85}Rb experiments, light from the positive first order high frequency AOM provides one beam as above. The second beam is passed through a separate, low frequency, AOM to achieve the required splitting of 3.035 GHz.

III. SYSTEM PERFORMANCE

The optical heterodyne spectrum between the two output beams is shown in Fig. 3. We perform this beam beating experiment by combining the two beams with a polarizing beam cube, passing the resultant beam through a polarizer and then fiber coupling the light to a high speed detector (Advanced Optical Components HFD6180-413). The microwave signal is then mixed down to 30 MHz to permit hertz level analysis. The main figure shows the beat note with a 1 kHz span. The inset figure shows the same signal on an 11 Hz span. We measure a full width at half maximum (FWHM) of 1 Hz from the inset data and posit that this is an upper limit defined by the resolution of our spectrum analyzer (HP 8560E).

In many experiments, the two photon detuning from resonance is scanned to determine the frequency dependence. While the AOMs have a scanning bandwidth of 150 MHz, in a double pass configuration this is reduced by a factor of $\sqrt{2}$. Also, slight shifts in the angle of the output beams from the AOMs reduce coupling into the TAs, further reducing the bandwidth of our overall system. We measure a 3 dB point of 53 MHz. This narrowed bandwidth may be an issue for experiments where large scans of the frequency difference are required.

It is important to note that in situations where the atomic system is very susceptible to small amounts of resonant light (i.e., in a dipole trap), cavity filtering may be required to thoroughly remove background ASE. We find that, because the ASE is in a different spatial mode, 1% of light coupled into a single mode fiber consists of unwanted frequencies.

IV. SUMMARY

We have presented an apparatus capable of generating high-power laser light with gigahertz splitting, designed for addressing the ground state hyperfine levels in rubidium 87. As the light is derived from a single source, the relative frequency stability is at the hertz level. This is accomplished using a system of parallel operating frequency shifters and semiconductor tapered amplifiers. The described system is capable of output light levels in excess of 1 W in each frequency component. This design provides better than an order of magnitude improvement in the available optical power over existing systems.

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