Wideband, Efficient Optical Serrodyne Frequency Shifting with a Phase Modulator and a Nonlinear Transmission Line

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Abstract: We report shifting of the frequency of an 850 nm laser with an instantaneous bandwidth of (350-1650) MHz and an efficiency between 35\% (minimum) to 80\% (best at frequencies around 600 and 1500 MHz) by phase modulation with a sawtooth waveform ("serrodyne frequency shifting"). We use a fiber-coupled traveling wave electro-optical modulator driven by a nonlinear transmission line.

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1. Introduction

Shifting the frequency of a laser is important for many applications in, e.g., atomic, molecular and optical physics, optical measurement, laser frequency and phase stabilization [1], optical gyroscopes [2], coherent optical communication systems [3], or spectroscopy. Tunable lasers can often replace such frequency shifters especially when a large frequency shift is desired [4]. However, this technique may require phase-locking, be costly, and have a slow response time. Acousto-optic modulators (AOM) [5] are commercially available for frequencies between $\sim 30 - 2500$ MHz, and achieve high efficiency especially for models up to 200 MHz. However, their tuning range is limited to a relatively narrow ($\pm 10\%$) band around the center frequency of each individual model, even if the deflection angle change is compensated for in a double-pass configuration. A good example for what can be achieved with such double-pass AOMs is described by Donley et al. where the peak efficiency is 75\% and the tuning bandwidth is 68 MHz full width at half maximum power for light coupled into a single-mode fiber [6]. On the other hand, electro-optical phase modulators (EOMs) can be used to transfer power into sidebands that are symmetric around the frequency of the laser. The frequency shift of the sidebands is in principle variable, but the maximum power transferred to any output frequency is limited to about 33\% with sine wave modulation [5].

Optical serrodyne frequency shifting theoretically allows one to achieve a wideband frequency shift with high efficiency [7]. The idea is to use an EOM for applying phase modulation with a sawtooth waveform. Driving the EOM with a perfect sawtooth waveform in theory shifts the frequency of the optical signal with complete suppression of undesired sidebands [7] and 100 \% efficiency. Previously shifts with electronically generated sawtooth waveforms have been reported in the MHz range [2, 7, 8]. A larger shift of up to 1.28 GHz has been reported with a generation of the sawtooth waveform that involved a photonic arbitrary waveform generator [9]. However, this not only requires the use of a femtosecond laser, but also limits the agility of the frequency changes, since the sawtooth period depends on the repetition rate of the laser pulses. Optical serrodyne frequency shifting has been utilized to achieve heterodyne self-mixing in a distributed-feedback fiber laser for use in a coherent detection system [10]. Serrodyne frequency shifters based on multistage phase modulation have been demonstrated [11].

Here, we describe an entirely electronic method of generating the sawtooth waveform, utilizing a nonlinear transmission line (NLTL). It has the benefit of being much simpler and cheaper to set up than the above photonic method while achieving even larger shifts. We report frequency shifting of an 850 nm laser by (350-1650) MHz using a fiber-coupled travelling wave electro-optical modulator driven by a NLTL. We experimentally demonstrate an efficiency of 35\% (minimum) to 80\% (best at select frequencies around 600 and 1500 MHz). Within these frequency ranges, the magnitude of the frequency shift can be instantaneously tuned because it is given by an rf sine wave generator.

2. Description

Figure 1 shows the experimental setup. It can be broken down into two main parts: First, the serrodyne shifter, which consists of the electronics and the EOM and second, an interferometer that we use to characterize the frequency shifting by a beat note measurement.

Our serrodyne shifter consists of the fiber-coupled EOM and the sawtooth generator based on the NLTL and associated drive electronics. The EOM is a lithium niobate modulator (PM-0K5-10-PFU-PFU-850-UL by EOSpace) with pigtailed polarization-maintaining fibers connected
Fig. 1. Diagram of Experimental setup

to both the input and output of the crystal. Our particular modulator is specified for a 0-12 GHz bandwidth with less than 2 dB variation in modulation efficiency. The half-wave voltage is specified as 2.3 V at 1 GHz. The specified optical insertion loss is 2.4 dB, corresponding to 58% overall optical transmission from input to output; we typically achieve 50%. The EOM’s rf input is driven by the signal from the output of a monolithic gallium arsenide nonlinear transmission line (model 7103 and 7113 “comb generators” by Picosecond Pulse Labs). In the basic setup (see Figure 1), the NLTL is driven with a sine wave created by a HP 8665A Signal Generator that is amplified to $\sim 20$ dBm using a Mini-circuits ZFL-2500VH+ amplifier.

The NLTL is basically a ladder of inductors and semiconductor diodes which function as voltage-variable capacitors [? , ?]. When a sine wave propagates through the NLTL, the higher voltage parts of the signal propagate faster than the lower voltage parts. This is because the capacitance of the diodes is reduced by the applied voltage which, in turn, speeds up the signal propagation through the NLTL. This dispersion distorts the sine waveform input into an approximate sawtooth waveform. The polarity of the diodes in our NLTLs is such that positive-going ramps are obtained. Obtaining negative ones would require a NLTL with the opposite polarity.

We use optical heterodyne detection to measure the frequency shift induced by the electro-optic modulator. We use laser light from a grating-stabilized diode laser at a wavelength of 850 nm that arrives at the experiment via a single mode fiber optic cable. Approximately half of this light is split off by a polarization beam splitter and coupled into the serrodyne shifter, with its polarization matched to the EOM.

The other half of the laser power is frequency shifted by $\omega_{AOM} = -2\pi \times 108$ MHz with an acousto-optical modulator and overlapped with the serrodyne shifter’s output on a beam splitter, where the two beams interfere. A New Focus 12 GHz amplified photoreceiver detects the heterodyned signal. The output signal of the photoreceiver is connected to a HP 8591A spectrum analyzer with an input range of DC-1.8 GHz. In our particular setup, the frequency shift of the EOM is positive, $+\omega_{EOM}$, so the observed beat frequency by the spectrum analyzer will be $\omega_{AOM} + \omega_{EOM}$.

3. Results

We measure the efficiency of the frequency translation as the ratio of the power in the desired sideband to the power of the carrier without the phase modulation. Note that this definition does not include fiber coupling losses. For some applications, fiber coupling is required anyway; in
In this case, there is very little additional loss since the EOM with fibers is almost as efficient as a bare fiber (50-80%, depending on the quality of the input beam). For optical serrodyne frequency shifting, the efficiency will depend on how well the amplitude (peak value) of the RF input matches the half wave voltage of the phase modulator, and any distortions in the sawtooth [14].

We first characterize the efficiency obtained with the 7103 NLTL driven by a constant amplitude sine wave signal. Figure 2 depicts the efficiency as a function of the frequency shift with sine wave input signals for 3 constant amplitudes. Using a drive of -3 dBm, we achieved an efficiency of 60% and a bandwidth of 200-1500 MHz full width at half maximum for the shifted power.

![Frequency vs. Efficiency of Input Sine Wave Signal for 7103 NLTL](image)

Fig. 2. Efficiency measured using the 7103 NLTL versus frequency for 3 different constant amplitude sine wave signals from the signal generator.

The efficiency data shown in gray in Figure 3 were obtained using the model 7103 NLTL. For each frequency, we optimized the efficiency by varying the amplitude of the sine wave input to the amplifier (between -10 to +13 dBm). For frequency shifts in the range 350 MHz to 1.65 GHz, we obtain more than 35% efficiency. The maximum efficiency (at 1250 MHz) was 61%.

The data shown in black in Figure 3 were taken using the 7113 model NLTL. We again optimized the amplitude of the input sine wave for each frequency. We also found that by varying the power supply voltage between 9 and 15 V for the Mini-circuits ZFL-2500VH+ RF amplifier, an improved efficiency could be obtained. This improvement of performance is supposedly due to the distortion of the sine wave by the amplifier which helps create a better sawtooth voltage at the NLTL output. We achieved a 1.5 GHz frequency shift with 80%. Relative to constant-amplitude drive (Fig. 2), these data show either higher peak efficiency (>70% in bands around 600, 800, 1000 and 1500 MHz) or greater uniformity (>40% for 350-1650 MHz).

For shifts below 1.25 GHz, a further improvement in efficiency could be achieved by adding the first harmonic of the drive frequency to the sine wave with adjustable amplitude and phase. This results in a rough approximation of a sawtooth delivered to the input of the NLTL, which then generates a higher quality sawtooth at its output, see figure 4. The harmonic is generated using a frequency doubler (ANZAC DI-4). To adjust the amplitude and phase, we use a variable delay line and a variable attenuator. The fundamental frequency and the harmonic are combined in a Mini-circuits power combiner (ZFSC-2-2). The combined signal is amplified with a Mini-circuits ZFL-1000VH and drives the model 7103 NLTL which is connected directly to the EOM.
Fig. 3. Performance of the two NLTLs when the input waveform is optimized for each frequency as described in the text.

RF port.

Fig. 4. Waveform after the 7103 NLTL as measured by a Tektronix 7904 oscilloscope equipped with an S-2 sampling plug-in (75 ps specified risetime) with a 20 dB attenuator. Input to the setup was 700 MHz sine wave. The obtained efficiency of the resulting frequency shift was 68%.

Although in this configuration, the amplifier and the power combiner are used far beyond their specified frequency range, we achieved 80% efficiency at 600 MHz and better than 50% efficiency in the range of 450 MHz to 1.25 GHz. At higher frequencies, our amplifier cannot pass the harmonic because its frequency is far beyond the specifications of the amplifier. For each data point, we optimized the amplitude of the input sine wave (12 to 20 dBm), the input power to the amplifier (7 to 15 V), the length of the linear delay line, and the attenuation on the variable attenuator (0 to 7 dB), see figure 5.

**Distribution of the power among sidebands** The power not shifted into the desired sideband is distributed between the original input frequency and other (undesired) sidebands. In one particular measurement, this distribution (in dB) was measured as shown in Tab. [1]. The setup used
for taking this data had a small frequency shift of 8.2 MHz, to allow for accurate data taking out to the highest sidebands. However, the data should be representative of the distribution of the power in serrodyne shifting when the efficiency is about 75%.

Table 1. Power in dB referred to the total power for various sidebands. The -1.26 dB for the 1st sideband indicates a 75% shifting efficiency.

| Sideband # | 2  | 1  | 0  | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 | -9 |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Power [dB] | -20| -1.26| -17| -15| -14| -15| -15| -17| -17| -17| -18| -18|

4. Conclusion

In summary, we have presented a wideband serrodyne frequency shifter based on a lithium niobate phase modulator and a nonlinear transmission line. We achieved frequency shifting of a 850 nm laser by with efficiencies ranging from 35% (minimum) to 80% over 1.5 GHz bandwidth. The current limitation on electronic sawtooth production is still the limiting factor in this class of phase modulators. This type of frequency shifter is ideally suitable to maintain constant detuning for large atom interferometry experiments and has many other potential applications.

Note Added: A similar implementation of serrodyne frequency shifting has been reported in Ref. [15].

5. Acknowledgements

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