Bridging the Optical and Microwave Frequencies with the Dual-frequency Faraday Laser

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***Abstract*—The dual-frequency Faraday laser, utilizing the two-peak transmission of a Faraday anomalous dispersion optical filter (FADOF), can achieve simultaneous lasing on two modes both determined by the atomic transition. The beating frequency between the two modes is close to the frequency interval between hyperfine energy levels of the atomic ground state. Since the frequency of the beat signal and output laser modes all depend on the cavity length, locking one of them can also improve the stability of the others. Therefore, by locking the beat frequency to a stable microwave frequency reference, the stability of the reference can be transferred to the laser frequencies; Similarly, locking one of the output laser frequencies will also transfer its stability to the beat frequency in the microwave regime. This can serve as a means to bridge the gap between the optical and microwave frequency regimes, and can have wide applications, such as absolute frequency measurement of a laser, or photonic microwave generation.**

Keywords—Faraday anomalous dispersion optical filter (FADOF), diode laser, faraday laser, dual-frequency laser, frequency stabilization

I. Introduction

The Faraday anomalous dispersion optical filter (FADOF) utilizes the Faraday rotation effect to achieve high noise rejection [1, 2], narrow bandwidth [3,4] and high transmission. Since the FADOF only allows light with frequency near the atomic resonance to be transmitted [5], it can effectively block out the background noise from the desired signal. Therefore, FADOFs see wide application in lidar technology [6, 7], optical communications [8, 9] and laser frequency stabilization [9-12].

The Faraday laser is a type of extended cavity diode laser that uses a FADOF as the intra-cavity frequency selection element [13, 14]. Since the laser frequency is determined by the transmission profile of the FADOF, it is immune to current and temperature fluctuations of the laser diode [15,16]. When the intra-cavity FADOF has two transmission peaks of similar strength, the Faraday laser can achieve simultaneous lasing on two laser modes. Our group has realized a frequency tunable dual-frequency (DF) Faraday laser lasing on two modes, their frequencies lying in the transmission peaks corresponding to the $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{3/2}$ and $6^2S_{1/2}(F = 3) \rightarrow 6^2P_{3/2}$ transitions of cesium, respectively [17].

In DF lasers, the beat frequency can be used to stabilize the cavity length, and subsequently improve the frequency stability, as seen in the DF He-Ne laser [18] and the DF Tm:YAG laser [19]. Therefore, by phase locking the DF beat frequency to a high-stability microwave frequency reference, with the feedback signal sent to a piezoelectric ceramic (PZT) to stabilize the cavity length, the frequencies of the two output modes can be stabilized to the same fractional frequency stability as the microwave reference. Additionally, by stabilizing the DF laser's output frequency, the frequency stability of the output modes is transferred to the beat frequency, therefore serving as a high-stability microwave source.

Here, we propose to use the DF Faraday laser as a link between the optical and microwave frequency regimes. In this application, the DF Faraday laser has the advantage that its two output modes each corresponds to an atomic transition [17]. Therefore, the beat frequency is close to the ground state hyperfine transition frequency, and a high-stability microwave frequency reference can be readily obtained. In addition, stabilizing the output laser frequency can be achieved via locking one of the output modes to the corresponding atomic transition via saturation absorption spectroscopy (SAS) or modulation transfer spectroscopy (MTS).

II. Experimental Setup

The experimental setup for using the DF Faraday laser for microwave-to-optical frequency transfer is shown in Fig. 1. This setup utilizes phase locking of the DF Faraday laser's beat frequency to a high-stability microwave reference, to create a DF laser that can serve as a means for optical frequency measurement. Due to the beat frequency f_{beat} and the two output laser frequencies f_1 and f_2 being integer multiples of the cavity mode free spectral range (which is $c/2L$, where L is the cavity length), the frequencies of the DF output laser modes can be calculated from the beat frequency. By phase-locking the beat frequency to a high-stability microwave reference, the stability is transferred to the output laser frequency. This can serve as

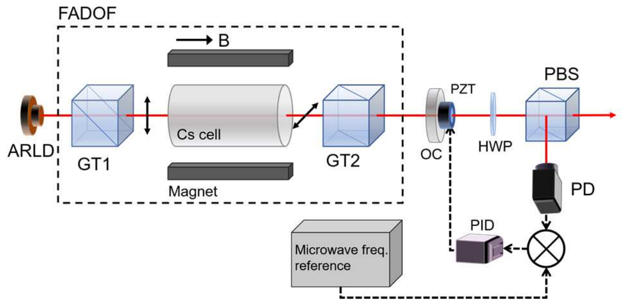

Figure 1. Proposed setup for stabilizing a DF Faraday laser by locking the beat frequency to a microwave reference. The DF Faraday laser is composed of an 852 nm antireflection-coated laser diode (ARLD), a Faraday anomalous dispersion optical filter (FADOF), and an output coupler (OC). The FADOF consists of two orthogonal Glan-Taylor prisms (GT1 and GT2), a cesium cell, and permanent magnets. By phase-locking the beat frequency to a high-stability microwave reference, the stability is transferred to the output laser frequency. This can serve as the basis for absolute frequency measurement via heterodyne detection.

the basis for absolute frequency measurement scheme via heterodyne detection. Another application of this setup is to utilize the DF laser output as a carrier for the microwave frequency standard, and the microwave signal can simply be extracted by using a photodetector to measure the beat note between the two DF laser modes. Such a simple setup will enable free-space dissemination of a microwave frequency reference.

In our second application, we use MTS to lock the frequency of one of the DF Faraday laser's output laser modes, as seen in Fig. 2. With the cavity length stabilized, the beat frequency can have the same stability as the output laser modes, therefore serving as a high-stability microwave source. This is a significantly simpler setup than traditional optically generated microwave setups, which use an optical frequency comb to transfer the stability of a PDH-locked laser to the comb's repetition frequency. In comparison, the MTS-stabilized DF Faraday laser can be much more robust and compact. In addition, by being referenced to an atomic transition via MTS, the DF Faraday laser can achieve better long-term stability than conventional setups for optically generated microwave.

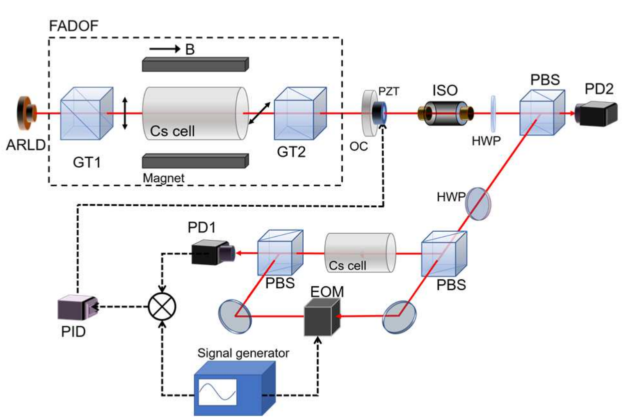

Figure 2. Proposed setup for utilizing a DF Faraday laser as a photonic microwave source. By stabilizing the laser frequency with modulation transfer spectroscopy (MTS), the beat frequency between the two output modes has the same stability as the output laser. Therefore, the beat signal from photodetector PD2 can serve as a high-stability microwave source.

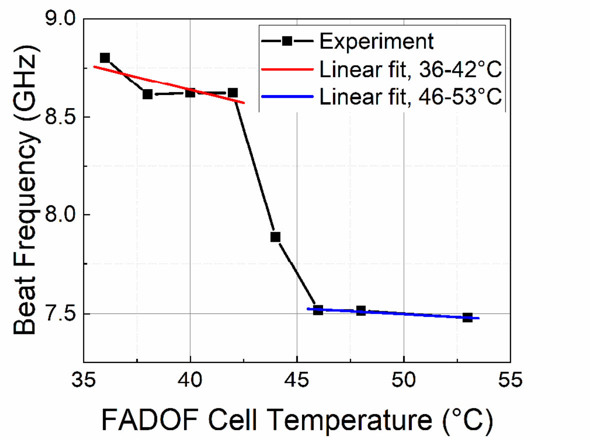

Figure 3. The beat frequency of the DF Faraday laser with different FADOF cell temperatures. When the cell temperature changes from 46 °C to 53 °C, the beat frequency is tuned from 8.80 GHz to 7.43 GHz.

III. RESULTS

We measured the frequency and linewidth of the beat signal of a free-running DF Faraday laser under various conditions. By adjusting the temperature of the FADOF's cesium cell, the beat frequency is continuously tunable between 7.43 GHz and 8.80 GHz, as shown in Fig. 3. The beat signal linewidth of the free-running DF Faraday laser is on the order of 1 kHz, never exceeding 2 kHz. Fig. 4 shows a typical beat signal with the FADOF's cell temperature set at 40 °C, the fitted Lorentzian linewidth is 0.6 kHz. Fig. 5 shows the SAS and MTS spectrums of the cesium $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{3/2}$ transition.

IV. DISCUSSION

Due to the Faraday laser's immunity to laser diode current and temperature changes, the DF Faraday laser can only be stabilized via feedback to the PZT adjusting the cavity length. This puts a limit to the frequency stability of the DF output modes, especially when attempting to lock the laser frequency to an atomic transition via MTS, since the PZT only has a limited bandwidth and can't suppress higher-frequency noise. To overcome this issue, PZTs with higher bandwidth must be employed, and the output coupler mirror of the DF Faraday laser must be light, in order to facilitate fast feedback.

V. CONCLUSIONS

In conclusion, we propose two experimental schemes that allows us to use the DF Faraday laser to serve as a means to bridge the gap between the optical and microwave frequency regimes. The first application transfers the frequency stability of a microwave frequency reference to the output laser modes of the DF Faraday laser by phase-locking the beat frequency. This can serve as the basis for absolute frequency measurement or free-space frequency transfer. The second application uses the beat frequency of a DF Faraday laser stabilized with MTS as a high-stability microwave source. Compared with conventional optically generated microwave setups, it has the advantages of robustness, compactness and better long-term stability.

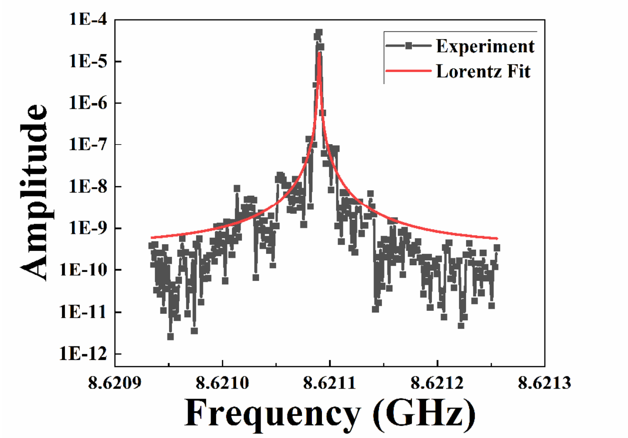

Figure 4. Spectrum of a typical beat signal of a free-running DF Faraday laser. The cell temperature of the FADOF is set at 40 °C, with a fitted linewidth of 0.6 kHz. The beating linewidth is expected to be narrowed to Hz level after the DF Faraday laser is frequency stabilized with MTS.

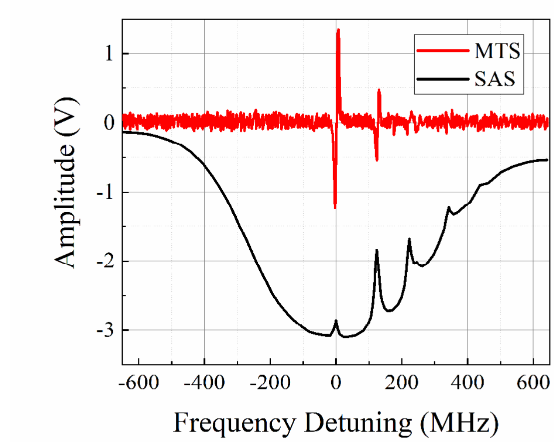

Figure 5. Saturation absorption spectroscopy (black-solid line) and corresponding modulation transfer spectroscopy (red-solid line) of the cesium $6^2S_{1/2}(F = 4) \rightarrow 6^2P_{3/2}$ transition.

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