A comparison of tunable, passively-stabilized two-frequency solid-state lasers for microwave generation

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Abstract— **We are developing tunable microwave sources based on a passively stabilized diode-pumped Nd:YAG laser. The laser operates on two orthogonal modes, which may be tuned by applying a voltage to an intra-cavity electro-optic crystal or by rotating an intra-cavity waveplate. We compare and characterize these alternative cavity designs in terms of power, tunability and noise.**

Index Terms— **YAG laser, heterodyning, microwave generation**

I. INTRODUCTION

Microwave photonics has attracted growing interest worldwide over the past few years. Applications such as fibre wireless networks and antenna arrays have attracted special interest and are the focus of much research in the field of microwave photonics. A relatively new application in this field has been the use of photonic devices for the generation of high frequency or widely tunable, high finesse microwave oscillators.

This paper presents a microwave source based on a two-frequency Nd:YAG solid-state laser. These lasers are ideal for the generation of low-power, high finesse, widely tunable microwaves. Using this approach two orthogonally polarized laser eigenmodes are heterodyned on a fast photo-detector or traveling photo-mixer to produce a microwave signal in the electrical domain.

Microwave generators have particular interest for electronic-warfare receiver applications. These applications require very low phase noise (in excess of -120 dBc/Hz [1]), wide frequency tunability and good long term frequency stability.

The two-frequency operation of a solid-state laser arises because YAG (like glass) is an isotropic material and can lase without a preferred lasing polarization in the absence of a polarization selective element, and, with minimal residual stress birefringence in the laser cavity. The introduction of birefringence into the cavity, such as by applying an electric field to an intra-cavity electro-optic crystal [2], [3], breaks the degeneracy in the longitudinal modes to create two simultaneous eigen-polarizations aligned along the introduced birefringence axes. This effectively causes a frequency difference because the effective cavity lengths are different for the two polarizations. These two orthogonal states can be coupled together and caused to beat to form a microwave sub-carrier at the difference frequency of the eigenstates. Selecting the amount of birefringence within the cavity can control the frequency difference between the two orthogonally polarized modes. This is usually done by either applying mechanical [4] or thermal stresses to the gain crystal, adding a number of waveplates [5] or by applying a voltage to an intra-cavity electro-optic (EO) crystal [3] such as lithium niobate or lithium tantalate.

In this paper, we compared the performances of two dual-mode solid-state laser arrangements. One being the helicoidal or twisted mode arrangement with two quarter-waveplates and the other is a linear arrangement using an electro-optic crystal (EO) as a birefringence controlling element. Section II describes in detail the experimental arrangement of the lasers, detection considerations, and typical results common to the two-frequency solid-state lasers. In Section III we show frequency tunability in excess of 1.8 GHz for the linear EO arrangement and approximately 700 MHz for the helicoidal arrangement. Noise and RF beat signal power is also investigated in this section. We conclude that each cavity design offers advantages under specific modes of operation.

II. EXPERIMENT

A number of cavities were set up as shown in Fig. 1. The electro-optic crystal cavity arrangement (Fig. 1(a)) uses a 6 mm long 1-at.% doped Nd:YAG gain crystal with HT @ 808 nm and HR @ 1064 nm dielectric coatings on one side and broadband anti-reflection coating on the other side, a 21 mm long z-cut $\mathrm{LiNbO_3}$ electro-optic crystal and an 1.5 mm uncoated etalon to prevent additional longitudinal modes oscillating. The output mirror was a 97% high reflector with a radius of curvature (RoC) of 7.5 cm.

The two orthogonal polarizations are generated in the linear EO cavity design by applying an electric field across the lithium niobate crystal. In this case the orthogonal modes align themselves parallel and perpendicular to the electric field lines in the EO crystal. The resulting relative frequency difference between the orthogonal modes is given by the optical path differences in the ordinary and extra-ordinary modes. The frequency separation therefore is

$$\delta\nu = \nu_0 \Delta n \frac{L_{EO}}{L} = \nu_0 n_o^3 r_{22} \frac{V}{d} \frac{L_{EO}}{L} \qquad (1)$$

where ν_0 is the laser center frequency, L is the cavity length,

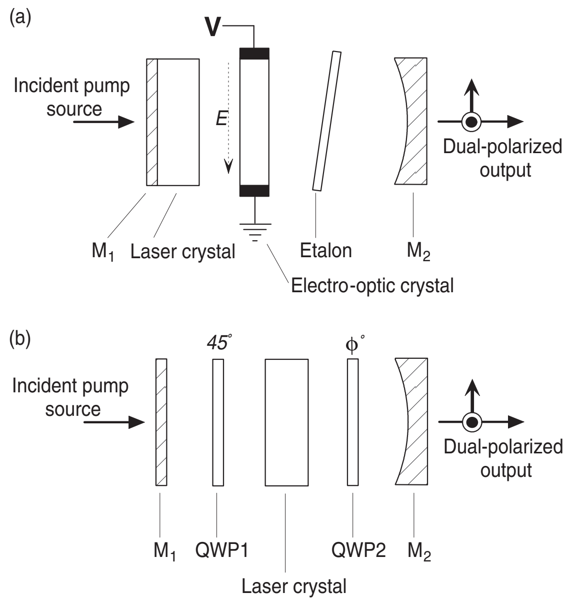

Fig. 1. Cavity arrangement for a linearly dual-polarized laser (top) and helicoidal twisted modes laser (bottom).

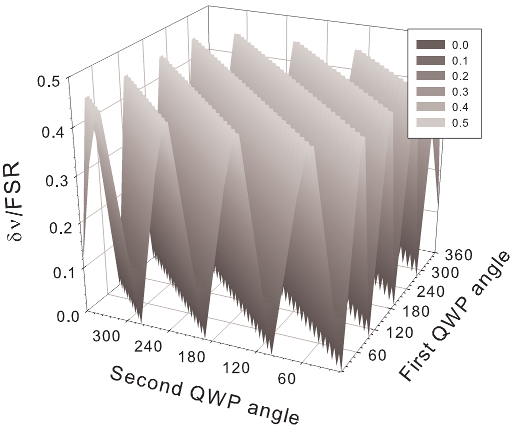

Fig. 2. Beat-note frequency tunability of the helicoidal arrangement with the fast axis rotation of two intra-cavity QWPs.

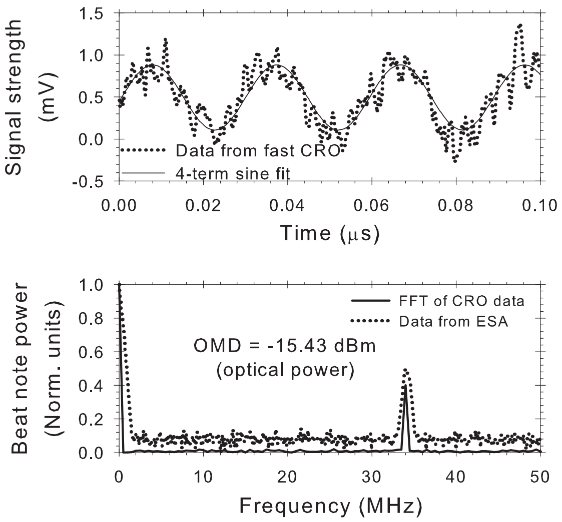

Fig. 3. Modulation depth based upon time-domain and frequency-domain measurements.

L_{EO}, r_{22} and $\frac{V}{d}$ are the length, electro-optic coefficient and the electric field applied to the lithium niobate.

The helicoidal cavity (Fig. 1(b)) used a longer (approximately 15 mm) piece of Nd:YAG with a 0.9-at.% dopant concentration with broadband anti-reflection coatings on both ends. Two quarter-waveplates (QWP) sandwiched the YAG crystal to form the helicoidal arrangement [6]. Pumping was achieved through an input mirror coated HT 808 nm/HR 1064 nm and the output coupler was the same as that used in the previous resonator (RoC= 7.5 cm, R= 97%). No etalons were needed in this resonator since the helicoidal arrangement sets up a standing wave eliminating possible spatial hole burning-related issues ensuring single longitudinal mode operation at low powers. Its operation, in terms of two-frequency operation, is most appropriately modeled by a generalized Jones calculus approach [7], using the resonance condition

$$M\overrightarrow{E} = \lambda\overrightarrow{E} \tag{2}$$

which tracks the polarization, amplitude and phase of the classical electromagnetic field $\overrightarrow{E} \equiv [E_x, E_y]^T$ over one cavity round trip (M). The frequency separation is then derived to give the tunability as shown in Fig.2.

Both cavities were pumped with a 100 μm fiber-coupled laser diode temperature-tuned to produce a stable 1–2 W of 808 nm pump output. One-to-one imaging of the pump into the Nd:YAG crystal allowed efficient operation. In addition a depolarizing waveplate was added to further ensure equal pumping of the orthogonal polarizations modes of the YAG laser.

The detection system consisted of two arms. The first included a half-waveplate (HWP), a analyzing polarizing beam splitter cube and a fast PIN photodiode connected to an electrical spectrum analyzer (ESA). The other arm had a confocal fabry-perot interferometer. A fast digital CRO was also occasionally used in conjunction with the ESA to investigate beat-note signals with relatively low frequencies.

III. RESULTS

Using the detection arrangement described above, we produced high frequency signals with optical modulation depths (OMD) exceeding 90% for the helicoidal laser and approximately 85% (OMD≈ -15.4 dBm) for EO crystal laser. Typical modulation depths for the EO crystal laser are shown in Fig.3.

The relative intensity noise (RIN) is a good method for characterizing the noise spectrum of any optical source and is inversely related to maximum bit rate and signal to noise ratio [8]. The RIN of the two-frequency EO crystal laser is shown in Fig. 4 and is similar to that of the helicoidal

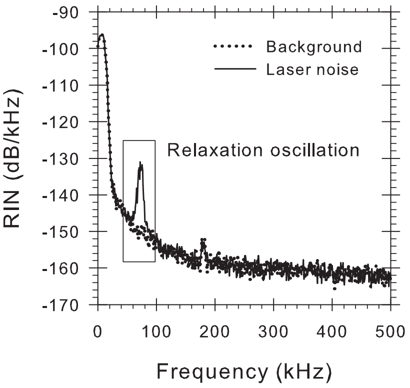

Fig. 4. Typical relative intensity noise of a two-frequency laser, note only one relaxation oscillation. Solid line represents the RIN of the lasers and measurement system combined and the dotted line represents the noise of the measurement system only.

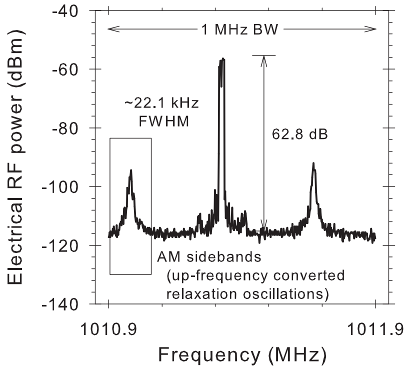

Fig. 5. Frequency spectrum of a typical 1 GHz beat signal from a two-frequency solid-state laser. Strong beat amplitude of approximately 62 dB and a free running full-width-half-maximum signal bandwidth of 22 kHz. Sidebands are amplitude modulated relaxation oscillations.

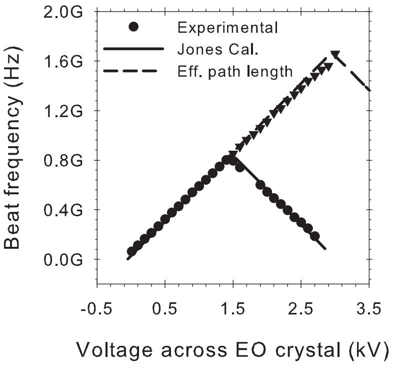

Fig. 6. Frequency separation of the two eigenpolarizations as a function of voltage across the lithium niobate crystal. The solid and dashed lines represent two theoretical models; solid uses a generalized Jones calculus approach; and dashed lines represent the predicted frequency separation using an effective optical path argument. Dots (both circles and triangles) represent experimental data points.

arrangement. It shows an extremely low RIN value and was measurement limited by our measurement technique and the resolution of the electrical spectrum analyzer. The relaxation oscillations (which are commonly to all lasers [9]) are clearly shown.

In traditional two-laser heterodyne techniques, one would expect to see two relaxation oscillations, one for each laser, however because of the weak coupling of the orthogonal eigenmodes [10] in two-frequency lasers only one relaxation oscillation is apparent (see Fig. 4) regardless of the power in each eigenmode.

A typical beat signal for the EO crystal laser is shown in Fig.5. The strong beat is common for both laser arrangements, but as is later discussed, is somewhat stronger for the helicoidal arrangement. The strength of the beat signal varies inversely with the frequency difference of the two eigenpolarizations. This particular arrangement gave a beat signal at 1 GHz, 62 dB above the noise floor with a free running full-width-half-maximum signal bandwidth of 22 kHz. Generally the beat strength ranges from 40–80 dB across the entire frequency tuning range. The amplitude modulations on either side of the beat-note signal are up-conversions of the relaxation oscillations.

Fig.6 showed the sub-carrier tunability for the electro-optically controlled two-frequency solid-state laser. The solid and dashed lines represent two theoretical models mentioned in Section II. The solid line shows results of the generalized Jones calculus approach for a single longitudinal mode; and dashed lines represent the predicted frequency separation using an effective optical path argument with multiple longitudinal modes. Both models provide comparable solutions.

In the linear dual-polarization arrangement and especially with the EO crystal laser, tuning the beat frequency beyond half the free spectral range (FSR) of the laser allows a possible second longitudinal mode to oscillate and mode hopping can occur. The fork in Fig.6 shows mode hopping, one can select which two orthogonal polarizations beat by careful tweaking of the intra-cavity etalon. As a result the EO crystal lasers are only restricted in their beat frequency tunability by (dielectric breakdown) voltage and the electro-optic material used.

Fig. 7 shows the tuning range of the helicoidal laser. The fast axis of the second QWP in the cavity was rotated about the cavity's optical axis. As expected from the generalized Jones calculus (see Fig.2) the beat frequency tunes over the complete range of half the FSR every 45 degrees.

There is on several peaks, evidence of slight mode hopping or tuning pass a half free spectral range. At angles away from the peak beat frequency, however the cavity quickly restores its correct beat frequency as derived from the general Jones calculus approach. It seems that this effect is perhaps a hysteresis effect or the result of residual birefringence in the cavity due to mounting and thermal stresses.

The beat amplitude of the helicoidal laser is also shown in Fig.7. The RF amplitude in comparison with the EO crystal laser is on average 10 dB larger. It has been reported that the

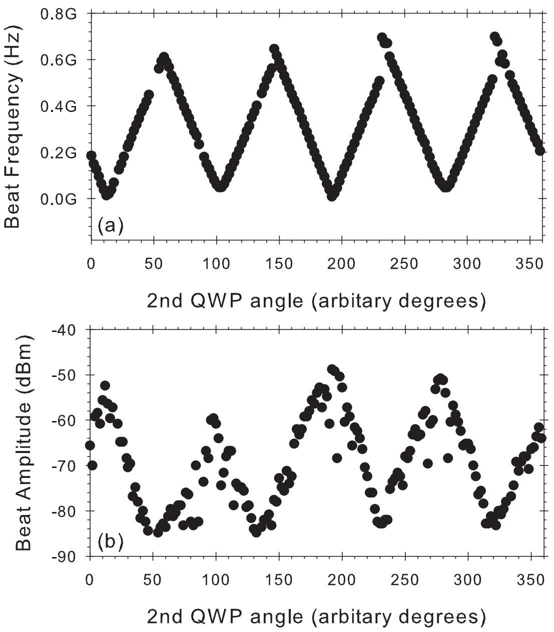

Fig. 7. Experimentally determined beat-note tuning by rotating the fast axis of the second QWP about the optical axis. Single longitudinal mode operation throughout tuning range and limited mode hopping at extreme frequencies.

coupling coefficients of a helicoidal eigenstates in solid-state lasers are twice that of linear eigenstates [10]. Although only empirical data exists, we believe the stronger coupling between eigenpolarizations in the helicoidal lasers produce the stronger beats.

IV. CONCLUSIONS

In this paper we have compared two complementary cavity designs, namely the linear dual-polarization EO crystal laser and the helicoidal two-QWP laser. Both lasers passively stabilized with good noise characteristics. We have also presented the tuning results for each laser. The EO crystal laser was able to be tuned to frequencies greater than half the FSR, whereas the helicoidal laser could not. Interestingly, the beat amplitude of the helicoidal laser demonstrated stronger mixing of the eigenpolarizations.

We are currently investigating the mechanisms of mode coupling in these and related cavities with a view to higher frequencies and greater microwave powers.

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