Tunable Terahertz Signals Using a Helicoidally Polarized Ceramic Microchip Laser

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***Abstract*—A two-frequency microchip laser based on highly doped ceramic Nd : YAG and twisted polarization modes is presented. The frequency difference between modes was tunable continuously over a frequency range of 150 GHz, from radio frequency to terahertz frequencies. This tuning is limited by the gain bandwidth of the Neodymium-doped YAG laser medium. The long-term frequency stability of the resulting narrow-linewidth beat-note signal is very good. This offers a simple, yet widely tunable terahertz source with potential for portable frequency reference applications.**

***Index Terms*—Ceramic lasers, laser stability, microwave generation, Neodymium : YAG (Nd : YAG) lasers, two-frequency lasers.**

THE FIELD of microwave photonics has attracted growing interest worldwide in recent years, with applications such as fiber wireless networks, phased antenna arrays, and optical techniques to generate high-frequency signals. Photonic-based microwave sources offer advantages in terms of phase noise, frequency tunability, and power scalability over external- or direct-modulation schemes. Here we present a photonic source based on a self-heterodyned, two-frequency, highly doped-polycrystalline neodymium yttrium aluminum garnet (Nd : YAG) laser, demonstrating the generation of high-finesse, stable, continuously tunable microwave, millimeter wave, and terahertz signals suitable for microwave photonics, optical interferometry and metrology, coherent sensing, and radio-over-fiber applications.

Two-frequency or dual-polarization operation in lasers arises because a globally isotropic gain medium, such as Nd : YAG [1], [2] and doped glasses [3], [4], may lase without a preferred laser polarization direction, in the absence of a polarization selective element and with minimal anisotropic cavity losses. In this situation, the laser experiences equal losses (and equal gain) on two orthogonally polarized modes, which oscillate simultaneously. When phase anisotropy is added to the isotropic resonator, the two modes oscillate at different optical frequencies, whose difference is proportional to the phase anisotropy. When these modes are heterodyned on a fast photodetector, the components of the eigenmodes beat together to produce an amplitude-modulated signal at the optical frequency difference, with wide frequency tuning [2], [3], low phase noise [4], and good long-term stability [5].

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Helicoidally polarized or twisted modes are dual-polarization modes that rotate along the optical path in the laser resonator and are formed when two phase-anisotropic components (e.g., quarter-waveplates) are added to an isotropic laser cavity. The first waveplate causes the modes, initially linear and orthogonally polarized on the cavity mirrors [6], to become circularly polarized. After passing through the second waveplate, the modes revert to linear polarization, orthogonal to the original polarizations. The electric vectors that define the polarization directions rotate through the cavity, hence the term helicoidal modes. The helicoidal modes, in addition to controlling the beat frequency, also suppress spatial hole burning in a similar manner to that in unidirectional ring lasers and hence maintain single longitudinal mode operation. Helicoidally polarized lasers also offer advantages of larger frequency separation between polarization modes of the same longitudinal mode index in comparison with similar dual-linearly polarized lasers [1]–[4], [7]. The maximum beat frequency in helicoidally polarized lasers is determined by the gain bandwidth and the resonator length. However, in dual-linearly polarized lasers, the amount of controllable birefringence in addition becomes a factor and beat frequency tuning is often limited well before the other two factors due to technical limitations (e.g., breakdown voltage of an electrooptic crystal).

Ceramic or polycrystalline materials incorporating dopants such as neodymium, ytterbium, erbium, and chromium have recently been developed as laser gain materials [8]. Although the first successful ceramic laser with reasonable efficiency was demonstrated by Ikesue *et al.* [9], we used polycrystalline materials grown using a vacuum sintering process and a liquid-phase chemical reaction in which a precursor reacts to form microcrystals which are sintered into ceramic YAG [10]. The final grain size is $\sim$10 to 20 μm although recently fine-grain ceramics with 2-μm grain size have been reported [8]. Optical properties such as the absorption and emission spectra, transition cross section, and lifetime of the upper laser state of ceramic Nd : YAG are very similar to those of Czochralski-grown crystals [8]. The mechanical properties of ceramic YAG are superior to those of crystalline YAG.

The key features of ceramic Nd : YAG over those of conventional single crystalline Nd : YAG for this work were the high doping levels and the improved coupling between orthogonal modes corresponding to enhanced self-heterodyne performance in ceramic lasers. The Nd concentration level in single-crystal Nd : YAG is limited to $\sim$1.5-at% because of the relative sizes of yttrium and neodymium atoms in the crystal lattice causing cumulative stresses [8]. However, ceramic Nd : YAG has been assembled into highly transparent structures with concentration levels of up to 10% [11]. Ceramic Nd : YAG with Nd concentration levels above a few percent surpasses the gain of Nd : YVO_4

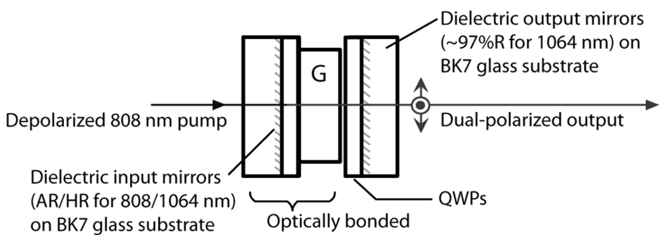

Fig. 1. Schematic of the laser setup. G is a 0.25-mm-long, 4% doped ceramic Nd : YAG plate; and QWPs are two true-zeroth-order quarter-waveplates optically bonded to dielectric coated glass substrates.

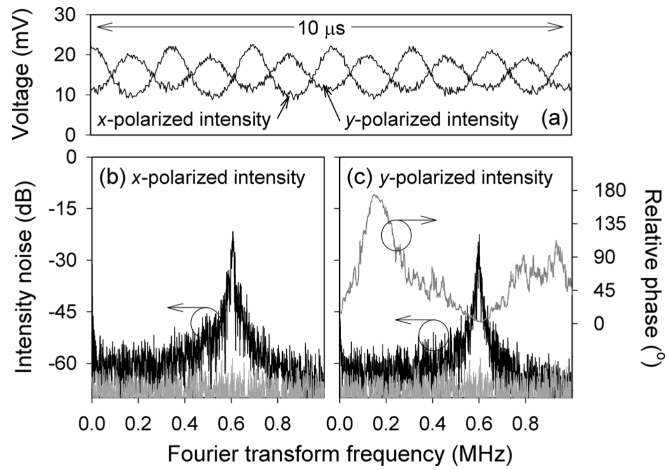

Fig. 2. Time series (a) and x- and y-polarized low-frequency intensity noise spectra (b), (c) highlighting ROs. The relative phase between orthogonal polarizations is also shown in Fig. 2(c) revealing a weak anti-phase RO near 150 kHz. Instrument noise is indicated in gray in (b) and (c).

with better thermal properties and transverse-mode profile for similar lengths and resonator designs. However, highly doped ceramic microchip lasers can suffer from poor beam quality, and quasi-periodic and chaotic instabilities because of localized nonorthogonal transverse modes lasing off individual, randomly oriented, highly doped crystallites [12], [13]. Overcoming or reducing the effects of these localized modes has generally been achieved by off-axis pumping arrangements, curved resonator mirrors [12], and pump-to-crystallite size matching [13]. It is, however, unclear whether these techniques can successfully be applied to all types of ceramics. Stable single longitudinal and dual-polarization-mode operation can be achieved if the beam quality is controlled. Another key feature of ceramic gain material is the enhancement of the self-heterodyne beat-note strength. A linear-dual-polarization ceramic laser when compared to an equivalent crystalline laser demonstrated more than 6-dB improvement of the power of the beat-note signal, proportional to the increase of the polarization-mode coupling constant [7]. This was attributed to the random crystallite structure of the ceramic material, leading to more efficiently coupled orthogonally polarized states via improvements of the gain overlap.

The experimental setup of the helicoidally polarized laser is shown schematically in Fig. 1. This laser consisted of a 0.25-mm-long highly doped (4%) ceramic Nd : YAG plate and two true zeroth-order quarter-waveplates, which were optically bonded to BK7 glass substrates with planar 1064-μm resonator mirror coatings on each waveplate. The ceramic plate was glued to the input waveplate-mirror, and the output waveplate-mirror ($R \approx 97\%$) was positioned close to the ceramic. Both the input waveplate-mirror and output waveplate-mirror were mounted in mechanized goniometers (with $>20^\circ$ rotation). The overall cavity length was estimated to be $\sim$300 μm.

This laser was pumped with an 808-nm depolarized beam focused to a 200-μm spot, which produced, at moderate pump levels ($\approx$200 mW), a cavity mode size of $\approx$250 μm (due to thermal lensing effects). Using a pump spot smaller than or closely matched to the thermally lensed cavity mode reduced the effects of localized transverse modes and gave moderate pump-to-laser efficiencies of 10% to 20% and output powers of $\approx$20 mW. At higher pump powers ($>$1 W), we observe more noise, which is attributed to the increased thermal lens and the decreased cavity mode size so that the pump region was greater than the cavity mode. Here additional localized modes oscillated due to the pumping of crystallites outside the fundamental cavity mode. These localized modes introduce additional noise which included quasi-periodic and chaotic instabilities as seen in [12] and [13]. Overall these localized modes reduced the beam quality of the laser.

At low powers, the microchip laser was well behaved, oscillating on a single transverse mode with typically two orthogonal polarizations depending on the relative waveplate angles. Beam propagation factor measurements, which relate to the number of transverse modes, were made for each polarization mode (using an inline polarizer to separate the polarizations) and for both polarizations together. Each polarization had an $M^2 \approx 1.2$ and the combined polarization had $M^2 \approx 1.3$ to 1.4.

The output of the laser was split into two paths. On one path, the polarization-sensitive intensity noise was monitored using two closely matched photodiodes and a polarization beam splitter. The waveforms were collected on a digital oscilloscope [Fig. 2(a)] and were postprocessed to yield the power spectra for each polarization, shown in Fig. 2(b),(c), respectively. The relative intensity noise of the laser was instrument-limited except at low frequencies near the relaxation oscillations (ROs), typical of most solid-state continuous-wave lasers.

A cross spectrum was also obtained from the individual polarized Fourier spectra which from the phase gave the frequencies of the in-phase RO and a much weaker anti-phase RO. [The anti-phase RO was obscured originally by noise in Fig. 2(b),(c).] By comparing the in-phase and anti-phase RO frequencies, a polarization-mode coupling constant [3] of 0.87 ± 0.03 was determined. This coupling constant is significantly higher than previously measured in ceramic Nd : YAG ($C \approx 0.72$, [7]), because the twisted modes within the gain material further improve the spatial overlap of the modes [14] and thus the beat signal [7].

At low frequencies ($<$6 GHz), the beat signal was monitored on a fiber-coupled InGaAs photodiode with a high-bandwidth deep-memory LeCroy oscilloscope. The polarized modes were scrambled in the fiber and the resulting signal across the photodiode was processed using a built-in power spectrum function of the oscilloscope revealing a strong, narrow-linewidth beat-note signal in the radio-frequency spectrum. The linewidth of the beat signal was fast Fourier transform-limited to less than 100 kHz and drifted (with a standard deviation at $\sim$1.6 GHz) less than 2 MHz over an hour period without active stabilization

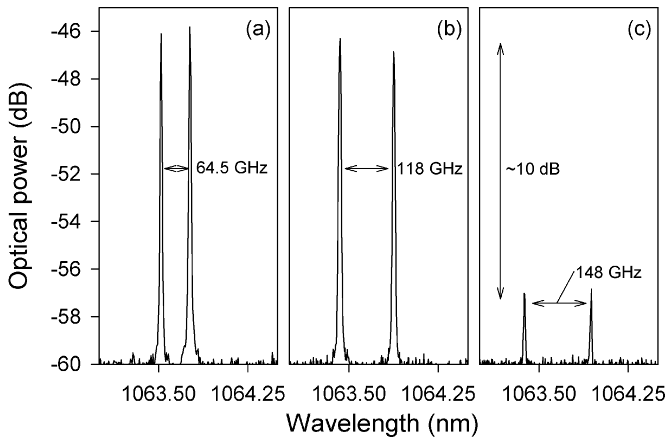

Fig. 3. Typical optical spectra of orthogonal polarizations measured on a high-resolution Advantest optical spectrum analyzer. Optical frequency differences of (a) 64.5, (b) 118, and (c) 148 GHz are illustrated.

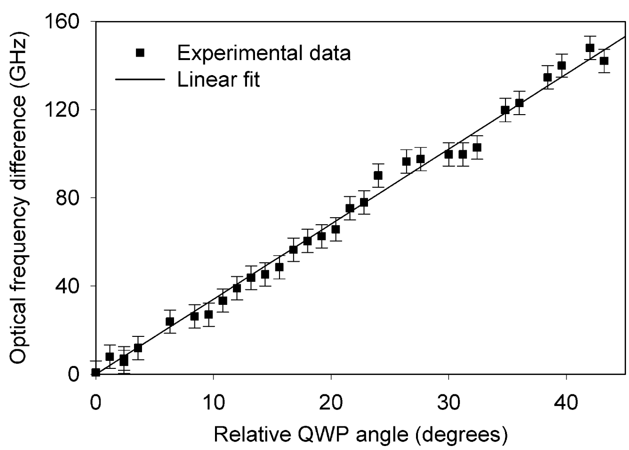

Fig. 4. Tuning of the optical frequency separation between orthogonally polarized modes as a function of relative quarter-waveplate angles. Error bars indicate the minimum resolution of distinct spectral features.

or feedback. The optical spectrum was also monitored using a fiber-coupled high-resolution Advantest optical spectrum analyzer with 10-pm ($\sim$2.4 GHz) resolution. Typical spectra of two simultaneously lasing narrow-linewidth optical modes with approximately equal optical power are shown in Fig. 3. By tuning the relative angles of the two quarter-waveplates, the optical frequency difference, shown in Fig. 4, was tuned linearly from a few gigahertz to $\sim$150 GHz. This trend is identical to those of beat signals measured by radio-frequency techniques using a fast photodiode and oscilloscope. At frequency separations $>$ 120 GHz [see Fig. 3(c)], the optical power in both polarizations decreased due to the limited gain near the edges of the spectral gain linewidth, which ultimately limited the tuning range in this device.

The highly doped ceramic dual-polarization microchip laser presented in this letter demonstrated good beat stability, strong beat signals and, because of the short cavities enabled by highly doped ceramic Nd : YAG, an ultrabroadband beat-frequency tuning range. By overcoming the poor beam profile and the chaotic intensity instabilities usually associated with highly doped ceramic Nd : YAG microchip lasers, this small helicoidally polarized laser, tunable continuously over a bandwidth of more than 150 GHz, offers a simple, widely tunable, stable photonic-based microwave to terahertz signal generator for portable, frequency reference applications. This laser has demonstrated the largest continuous dual-polarization tuning range of a single longitudinal mode reported to date in Nd : YAG and highlights possibilities of larger tuning ranges with optimal choice of gain materials (i.e., wider gain and spectral linewidths) and more compact cavity designs.

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