15 February 2001

OPTICS COMMUNICATIONS

ELSEVIER

Optics Communications 188 (2001) 353–357

www.elsevier.com/locate/optcom

# Dual frequency tunable cw Nd:YAG laser

L. Grossard *, A. Desfarges-Berthelemot, B. Colombeau, V. Couderc, C. Froehly

*Faculté des Sciences, Institut de Recherche en Communications Optiques et Microondes, UMR CNRS 6615, 123 Avenue A. Thomas, 87060 Limoges Cedex, France*

Received 9 August 2000; received in revised form 20 November 2000; accepted 12 December 2000

**Abstract**

A three-mirror laser, with very different spacings between the mirrors is studied numerically and experimentally. Two laser lines are emitted with a beat frequency in the tenths of GHz and a very fine tunability. © 2001 Published by Elsevier Science B.V.

*PACS:* 42.60.−v

*Keywords:* Laser resonator; Laser modes; Laser tuning; Optical generation of microwaves

## 1. Introduction

Considerable interest has been shown in the microwave generation by using the beating of optical frequencies [1–6]. For this purpose, the use of a diode pumped Nd:YAG laser is attractive providing that the carrier frequency is of no importance [7,8]: optical control of phased array radar is an example of application. In this case, the corresponding gain profile is of the homogeneously broadened type, and cw Nd:YAG lasers tend to oscillate only in a single frequency mode. However, several lines can simultaneously coexist inside the gain bandwidth, if they are emitted by different atoms of the laser medium. For instance, a solution to obtain dual frequency emission for beat frequency generation consists in performing a two parallel propagation axis laser called "forked laser" [6]. This solution is rather intricate because it requires polarization splitting of both pumping and laser beams.

In this paper, we consider the emission of two coherent lines with tunable frequency difference by a classical Nd:YAG laser with only one propagation axis. This is possible because the spatial hole burning (SHB) [9] creates population gratings that inhomogeneously broaden the gain [10]. Without any special precautions, the frequency difference $\Delta f$ between two adjacent modes created by SHB is fixed by the distance along which the pump beam and laser beam overlap.

Here, we propose to perform a dual wavelength laser for which $\Delta f$ is accurately adjustable on a large scale. This is obtained by putting inside the cavity a passive frequency filtering device.

* Corresponding author. Fax: +33-5-5545-7514.
*E-mail address:* grossard@ircom.unilim.fr (L. Grossard).

0030-4018/01/$ - see front matter © 2001 Published by Elsevier Science B.V.
PII: S0030-4018(01)00995-6

## 2. Principle of frequency control by intracavity filtering

Fig. 1 shows the multiwavelength Nd:YAG laser. The active medium, located at one end of the resonator, is longitudinally end pumped through a dichroic mirror $M_3$ by a cw laser diode beam. The mirror $M_3$ is totally reflecting for the Nd:YAG laser line. The second reflective element of the laser is not a single mirror as in classical lasers but a set of two plane and parallel mirrors $M_1$ and $M_2$ for filtering operation. A similar three-mirror cavity has already been studied and experimented by Pedersen et al. [11] to obtain a single tunable frequency emission [12].

In order to avoid transverse interference effects inside this Fabry–Perot type filtering device, the latter must be illuminated by a limited plane wavefront. This is obtained by placing the beam waist in the $M_3$ plane, at the focal length of the lens L. With such an arrangement, we effectively observed a $TEM_{00}$ emission due to tri-dimensional gain filtering in the laser medium without additional spatial filtering by any additional aperture.

The set of mirrors $M_1$ and $M_2$ may be considered as equivalent to a single mirror, with a complex amplitude reflectance $r_{eq}$ depending on the frequency $f$, according to:

$$r_{eq} = -\frac{r_2 + r_1 \exp \mathrm{j}\dfrac{4\pi f L_1}{c}}{1 + r_1 r_2 \exp \mathrm{j}\dfrac{4\pi f L_1}{c}} \qquad (1)$$

$r_1$ and $r_2$ are positive and real numbers and correspond to the reflectances of $M_1$ and $M_2$. The reflectance $r_{eq}$, given by relation (1), is a complex number whose modulus $|r_{eq}|$ and phase $\Psi$ (Fig. 2) depend both periodically (period $c/2L_1$) on the frequency $f$. One may also consider $\Psi(f)$ as the phase shift introduced by the reflection onto $(M_1 + M_2)$.

Without the amplifying medium inside the cavity, the resonant frequencies $f_q$ are given by the solutions of the equation:

$$\frac{4\pi}{c} f_q L_2 + \Psi(f_q) = 2\pi q \quad \text{(with } q \text{ integer)} \qquad (2)$$

With the amplifying medium inside the resonator, all the previous frequencies cannot be emitted. The selected ones result from simultaneous effects of laser homogeneous gain profile, spatial hole burning effects and losses depending on $|r_{eq}|$.

In the next paragraph, we report numerical determination of the three-mirror laser beat frequency $\Delta f$ adjustment by varying the lengths $L_2$ or $L_1$ between the mirrors. Then, experimental results are shown for comparison.

## 3. Numerical study of the dual frequency laser and experimental results

The considered arrangement is depicted in Fig. 1. Mirrors $M_3$ and $M_1$ have reflectivities of about 1 for the laser wavelength. The power reflectance of

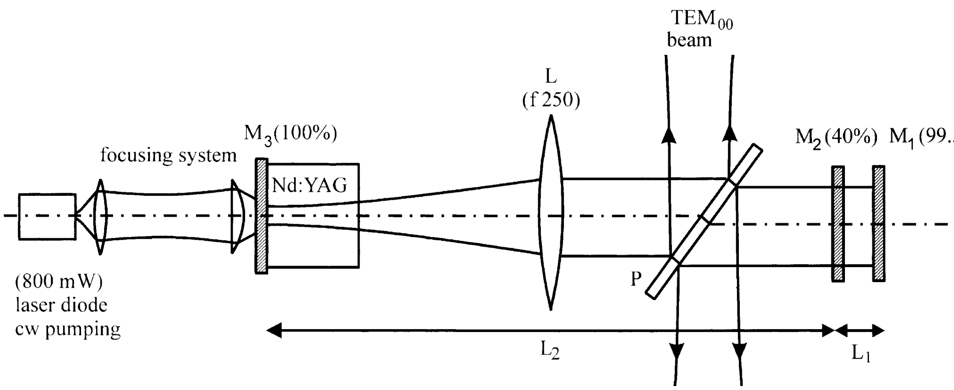


Fig. 1. Arrangement for dual frequency emission. $M_1 + M_2$: intracavity frequency filter; P: polarizing plate and output coupler.

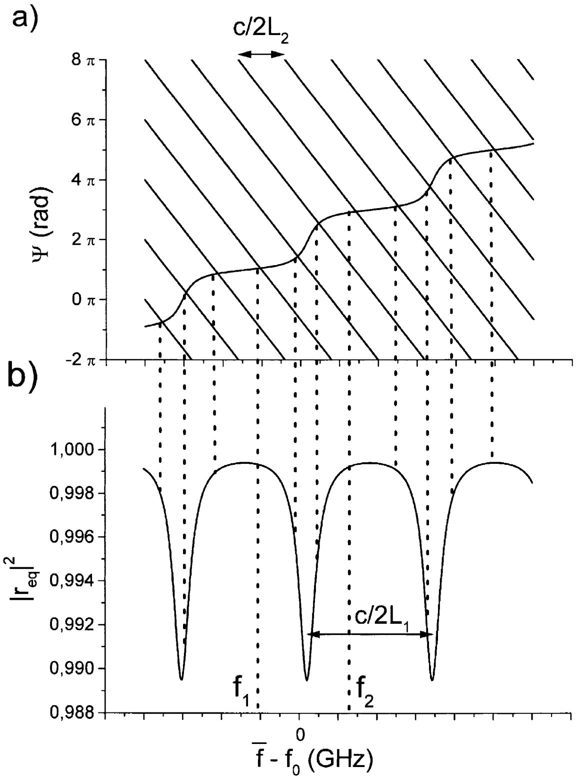


Fig. 2. Reflection by the set ($M_1 + M_2$) versus frequency. $r_{eq}$: reflection coefficient; $\Psi$: reflection phase shift; $R_1 = 0.995$; $R_2 = 0.4$; $f_0 = c/\lambda_0 = 2.82 \times 10^{14}$ Hz; $\lambda_0 = 1064$ nm.

$M_2$ was chosen equal to $R_2 = |r_2|^2 = 0.4$. The distance between mirrors $M_1$ and $M_2$ of the filtering device is $L_1 = 9.3$ mm, giving a free spectral range $c/2L_1 = 16.13$ GHz. The length $L_2$ between $M_2$ and $M_3$ will be chosen around 0.55 m.

In a first step, we compute the resonant frequencies $f_q$ of the three-mirror laser by looking for the intersections of the straight lines $y_{1,q}(f) = 2\pi q - 4\pi f_q L_2/c$ with the curve $y_2(f) = \Psi(f)$. Fig. 2a schematically shows these curves drawn with $L_2/L_1 \approx 2.5$ for the sake of figure clarity. In fact, $L_2/L_1$ was chosen equal to about 55 for the following numerical and experimental work. The resonant frequencies are not regularly spaced with the period $c/2L_2$ as in a classical resonator because of non-linear dependence of $\Psi$ versus $f_q$ but the whole frequency spectrum has a periodicity equal to $c/2L_1$. Fig. 3 shows the calculated frequency difference $f_{q+1} - f_q$ ($q$ integer) versus $\overline{f} - f_0$ with the mean frequency $\overline{f} = (f_{q+1} + f_q)/2$ and $f_0 = c/\lambda_0$, $\lambda_0 = 1064$ nm.

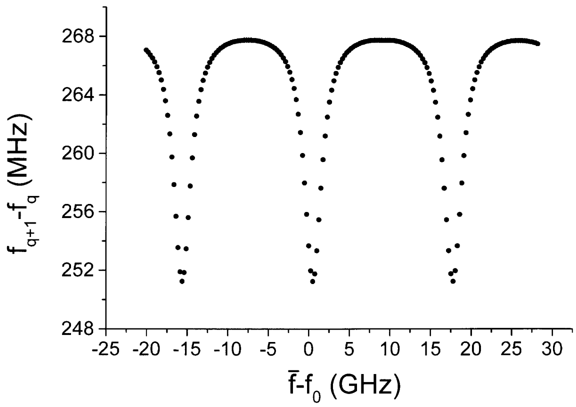


Fig. 3. Frequency difference $f_{q+1} - f_q$ for two successive modes of the empty resonator versus $\overline{f} - f_0$; $\overline{f} = (f_{q+1} + f_q)/2$; $f_0 = c/\lambda_0 = 2.82 \times 10^{14}$ Hz; $\lambda_0 = 1064$ nm; $L_2/L_1 = 55$.

In a second step, we decide to compute the frequencies emitted by the three-mirror laser, taking into account the losses due to the set of mirrors $M_1$ and $M_2$. Starting from resonant frequencies previously calculated, we compute, for each one, the value of $|r_{eq}(f_q)|$ and we keep only those for which $|r_{eq}(f_q)|$ has the highest values (Fig. 2b). In this way, we consider the fact that the laser line broadening is homogeneous. We thus obtain a set of frequencies because of periodicity of $r_{eq}(f)$. As we want only two laser lines giving one beat frequency $\Delta f$, we select the two frequencies ($f_1$ and $f_2$ on Fig. 2b) closest to the frequency $f_0$ for which the classical gain curve is maximum. Each resonant frequency depends on $L_2$ as shown in Fig. 2a. Consequently, $\Delta f$ is also connected to $L_2$. We have plotted the numerical value of $\Delta f$ versus $L_2$, keeping $L_1$ equal to 9.3 mm (Fig. 4). This figure shows that $\Delta f$ varies in a linear way versus $L_2$ over a range of about $c/2L_2 \approx 270$ MHz. Frequency jumps result from competition between two adjacent resonant modes given by Eq. (2).

An experimental validation of this behavior was performed under the conditions of the numerical study. A polarizing plate P was inserted between then lens L and the set of mirrors $M_1 + M_2$, reflecting a part of the intracavity laser beam because the Brewster law is not exactly satisfied. This reflected power forms the laser output. The

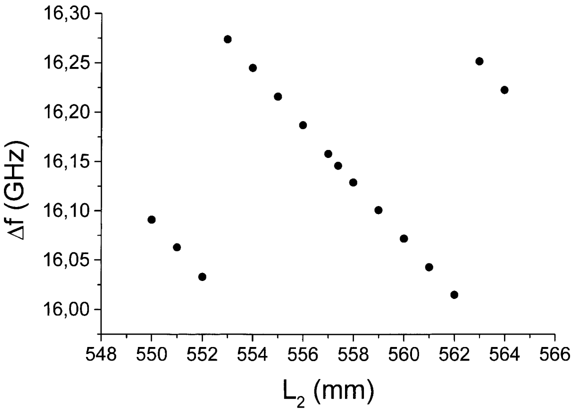


Fig. 4. Calculated beat frequency $\Delta f$ versus $L_2 = M_2M_3$, $L_1 = M_1M_2 = 9.3$ mm.

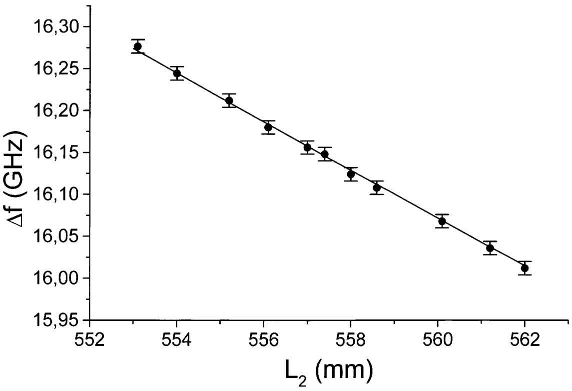


Fig. 5. Comparision between calculated (—) and measured (●) values of $\Delta f$. Error bars are due to spectrum analyzer resolution.

gain medium is a 1 cm long Nd:YAG crystal. With a pump power equal to 800 mW, only two modes were observed each one with a power equal to 2 mW. The corresponding beat frequency $\Delta f$ was measured thanks to an ultrafast photodiode "newfocus" model 1437 connected to a spectrum analyzer.

If we raise the pump power, more than two laser lines can coexist, with frequency separation about $\Delta f$.

In order to vary the beat frequency $\Delta f$ given by the two modes, the length $L_2$ between $M_2$ and $M_3$ was changed by translation of the set of mirrors $M_1$ and $M_2$, maintaining $L_1$ constant. Fig. 5 shows the experimental beat frequency (dots) versus the length $L_2$ and also the preceding numerical curve (continuous) for comparison. A very good agreement is obtained between experimental and numerical results. This agreement shows that the available gain for the two modes is independent of the frequency difference because no gain variation due to spatial hole burning was considered in the numerical study. As predicted by numerical analysis, we observed discontinuities due to mode competitions. Moreover, when adjusting very accurately $L_2$ around jumps of $\Delta f$, we could observe two simultaneous beat frequencies distant by 270 MHz.

The presence of the beat frequency $\Delta f$ in the photocurrent given by the photodiode is a proof of simultaneous emission of both frequencies by the laser. In order to estimate the coherence properties of the beat signal, we attempted to measure the beat frequency linewidth. For this purpose, we did spectral analysis with recovery times up to $\tau = 120$ ms, and frequency span equal to 500 kHz. Under these conditions, linewidth was found equal to 20 kHz at $-3$ dB, which is the value of the frequency impulse response of the spectrum analyzing device. Larger values of recovering times give no better frequency resolution because of various mechanical instabilities of the laser arrangement. However, each laser line and the beat line show high degrees of temporal coherence.

The interest of the three-mirror device lies in the ability to adjust finely $\Delta f$ by varying $L_2$. From Fig. 5, one can show that a variation of $L_2$ equal to 1 mm produces a relative variation of $\Delta f$ equal to 0.18% around 16 GHz. Assuming the lowest translation of the set of mirrors $M_1 + M_2$ equal to 5 μm, the lowest variation of $\Delta f$ is 150 kHz. If we consider for comparison a two-mirror laser cavity emitting two modes with frequency separation $\Delta f$ equal to 16 GHz, i.e. a cavity length of 9.3 mm, we verify that a translation of one laser mirror by 5 μm would produce a variation of $\Delta f$ equal to ≈8000 kHz.

With the three-mirror cavity, it is not possible to perform continuously a fine adjustment of $\Delta f$ on a large scale, by varying $L_2$ and keeping $L_1$

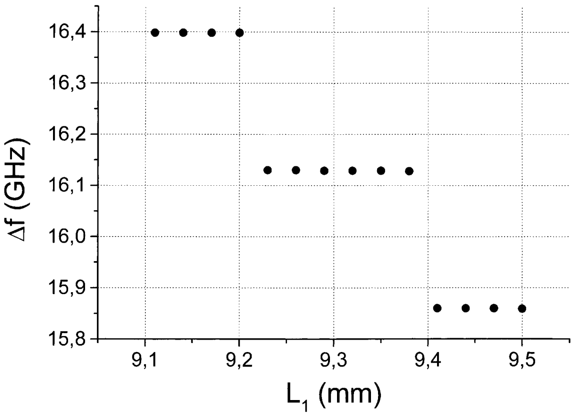


Fig. 6. Numerical calculation of beat frequency $\Delta f$ versus thickness $L_1$ of the intracavity filter, for $L_2 = M_2M_3 = 0.558$ m.

constant, as shown in Fig. 4. This calculated curve undergoes jumps of around 270 MHz for variation of length $L_2$ around $L_1 = 9.3$ mm.

If the intracavity filter thickness $L_1$ is modified by keeping the length $L_2$ constant, the beat frequency $\Delta f$ has a step behavior. Fig. 6 shows the effect on $\Delta f$ of a continuous change of $L_1$ around 9.3 mm with $L_2$ equal to about 558 cm: $\Delta f$ undergoes jumps of around 270 MHz. This behavior can be explained by competition between modes of the cavity formed by mirrors $M_2$ and $M_3$, whose free spectral range is $c/2L_2 \approx 270$ MHz.

By changing at the same time $L_1$ and $L_2$, it is possible to perform a continuous adjustment of $\Delta f$. This is obtained for the following relative variations:

$$\frac{dL_1}{L_1} = \frac{dL_2}{L_2} = -\frac{d\Delta f}{\Delta f} \tag{3}$$

Experimentally, we observed a frequency tuning from 10 to 40 GHz. The tuning range is theoretically limited by the Nd:YAG$^{3+}$ bandwidth. We noticed that for $\Delta f$ greater than 40 GHz, the frequency filter was not selective enough to suppress lines close to the gain bandwidth center and compatible with SHB. The performances of our adjustable two frequency laser are comparable, to our knowledge, to those obtained with similar systems [6]. However, it has the advantage of device simplicity.

## 4. Conclusion

The filtering properties of the three-mirror laser allow spatial hole burning effects control, and emission of several laser frequencies with desired difference. Close to laser threshold, we obtained only two frequencies with a high degree of temporal coherence. The laser was made of two adjacent cavities, one larger and one shorter. The interest of this arrangement is to obtain a rather large beat frequency $\Delta f$ thanks to the short cavity, and simultaneously a very fine tuning of $\Delta f$ by varying the thickness of the largest cavity. We obtained a frequency adjustment from 10 to 40 GHz with a beat frequency linewidth lower than 20 kHz at $-3$ dB (instrument limited). The tuning range could be extended by use of doped glasses.

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