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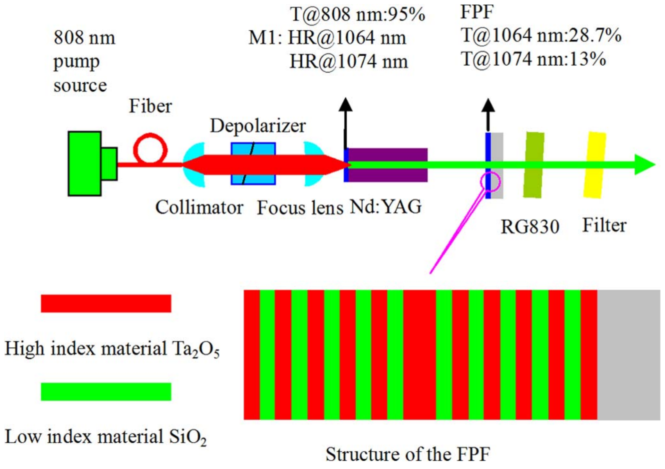

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A 1064- and 1074-nm Dual-Wavelength Nd:YAG Laser Using a Fabry–Perot Band-pass Filter as Output Mirror

X. Z. Wang,[1] Z. F. Wang,[1] Y. K. Bu,[1] L. J. Chen,[1] G. X. Cai,[2] and Z. P. Cai[1]

[1]Department of Electronic Engineering, Xiamen University, Xiamen 361005, China.
[2]Department of Electronic Science, Xiamen University, Xiamen 361005, China.

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Abstract: We propose and demonstrate a 1064- and 1074-nm dual-wavelength Nd:YAG laser by exploiting a dielectric Fabry–Perot bandpass filter (FPF) as laser output mirror. A fiber-pigtailed 808-nm laser diode array is used to pump an ⟨111⟩-cut Nd:YAG crystal with a plano-plano resonator cavity. The dielectric FPF as output mirror is specially designed to balance the net gain of 1064 and 1074 nm to obtain a dual-wavelength laser. Simultaneous dual-wavelength lasing at 1064 and 1074 nm is successfully achieved. The maximum output power of the laser is 581 mW, and the slope conversion efficiency is 18.8% with the threshold pump power of 2.1 W. The design of the FPF used as output mirror, including the relationship between FWHM and spectral separation, peak wavelength location, and peak transmission, are discussed. Compared with the coupled-cavity, etalon, or specially coated mirror methods, the FPF method presented in this paper is both easy in the selection of oscillating wavelength and simple in design and fabrication.

Index Terms: Diode-pumped lasers, solid state lasers, dual-wavelength.

1. Introduction

Dual-wavelength lasers have been of interest for practical applications such as remote sensing instruments, optical communication devices, laser ranging, topography, THz wave generation, as well as an abundance of medical uses [1], [2]. One of the methods to obtain a dual-wavelength laser is uses crystals offering simultaneous lasing on two wavelengths in a single ion [1]. Nd:YAG crystal is one of these kinds of crystals and is the most widely-used laser gain medium because of its excellent optical characteristics and mechanical properties. Many dual-wavelength lasers based on Nd:YAG crystals are investigated [3]–[9] and usually work in two different cavity designs. For large dual-wavelength separation situations (few tens of nm or more), coupled-cavity is usually used [3], [7]. For small dual-wavelength separation situations (few nm), either an etalon [5] or a specially coated mirror are usually used [4], [8], [9].

Among the achieved dual-wavelength Nd:YAG lasers, either the transitions of the dual-wavelength belong to two different upper and lower Stark energy levels [6]–[9], or the transitions of the dual-wavelength share the same upper Stark energy levels but with different lower Stark

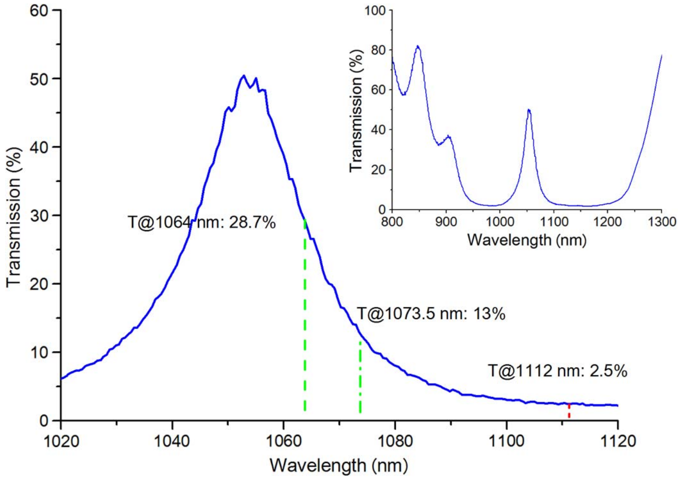

Fig. 1. Detail transmission curve of the Fabry–Perot filter (FPF) around 1064 nm. The inset shows the measured transmission outline of the manufactured FPF.

energy levels [1], [3]–[5]. To the authors' knowledge, there is no report of a dual-wavelength Nd:YAG laser with transitions sharing the same lower laser Stark energy level.

The coupled-cavity and etalon methods make the cavity complicated, while the specially designed mirrors have complex designs and demanding coating fabrication. In contrast, a Fabry–Perot band-pass filter is a traditional device. The pass band of a Fabry–Perot filter (FPF) can be used to balance the net gain and obtain dual-wavelength oscillation in a laser, which may substitute for the special coating mirror or etalon methods. In this paper, we use a Fabry–Perot band-pass filter as output mirror for an $\langle 111 \rangle$-cut Nd:YAG crystal laser. The Fabry–Perot filter is specially designed to balance the net gain of 1064 nm and 1074 nm to obtain a 1064 nm and 1074 nm dual-wavelength laser. The 1064 nm corresponds the transition from R2 to Y3, the 1074 nm corresponds the transition from R1 to Y3, so they share the same lower laser Stark energy level. To the authors' knowledge, it's the first time a 1064 nm and 1074 nm Nd:YAG dual-wavelength laser is demonstrated. Furthermore, it's also the first time a specially designed Fabry–Perot band-pass filter is used as output mirror of a laser cavity to obtain a dual-wavelength laser. The design of the FPF, the experimental setup and theoretical analysis are introduced in Section 2. The experimental results and analysis are presented in Section 3, followed by a brief conclusion in Section 4.

2. Filter Design, Experimental Setup, and Theoretical Analysis

Fabry–Perot band-pass filter (FPF) is usually an all-dielectric filter consisting of quarter-wave optical thickness layers for the mirrors and half-wave optical thickness or multiple half-wave optical thickness layers for the spacers [10]. In this paper, a single cavity Fabry–Perot band-pass filter with pass band centered at 1052 nm is designed and fabricated. The single-cavity FPF is composed of quarter-wave isotropic layers of alternating high and low refractive indexes, denoted as H and L, respectively. The stacked layer structure is substrate /(HL)^5 2H (LH)^5 /air and the phase thickness values of H, L layers are all $\pi/2$ at 1052 nm. The substrate is a 3-mm-thick BK7 glass plate with parallel plane surfaces. The high refractive index layers are composed of tantalum oxide (Ta_2O_5) while the low refractive index layers are composed of silica (SiO_2). The two central high index layers form a half-wave spacer layer. The filter was deposited by a remote plasma magnetron sputtering process (System Control Technology S500). The measured transmission curve of the FPF is shown in Fig. 1, and shows that the peak transmission is 50.5% and located at 1052.8 nm, due to a slight error in the deposition rate. The transmissions at 1064 nm, 1074 nm, and 1112 nm are 28.7%, 13.0%, and 2.5%, respectively.

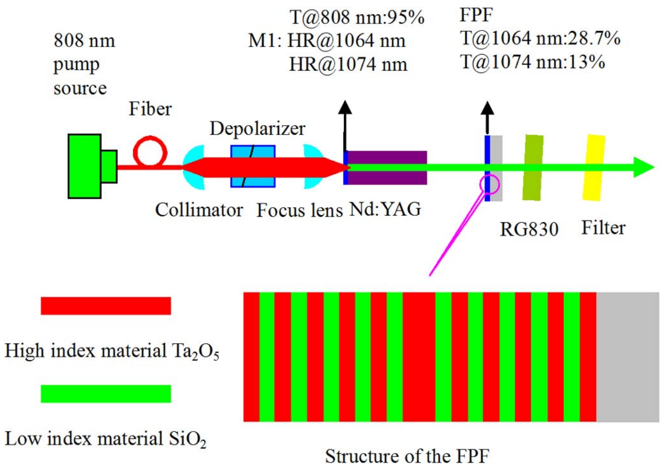

Fig. 2. Experimental setup.

The experimental setup is shown schematically in Fig. 2. Light from a fiber-pigtailed 808 nm pump source (LIMO) is firstly collimated and depolarized, then focused on the $\langle 111 \rangle$-cut Nd:YAG by a plano-convex lens ($f = 15.29$ mm). The diameter of the pump beam on the surface of Nd:YAG is about 190 μm. The 0.5% doped Nd:YAG (CASTECH INC.) is 3 mm × 3 mm × 8 mm, enclosed in indium foil and passively cooled in a copper block. The input surface of the Nd:YAG is anti-reflection-coated at 808 nm, 946 nm, 1319 nm and high-reflection coated near 1064 and 1074 nm, forming the front mirror (M1) of the laser cavity. The second surface of the Nd:YAG crystal is anti-reflection-coated around 1064 nm and 1074 nm. The FPF forms the output mirror for the 51 mm long laser cavity. The Fabry–Perot filter is installed on a 5-dimensional stage, which allows the FPF can be adjusted with the following five freedoms: X, Y, Z, tilt about X, and tilt about Y with high precision. The 5-D stage is fastened on a shockproof experimental table. The laser output is firstly filtered by a RG830 glass to absorb the residual 808 nm pump light, then measured by a power meter (COHERENT PM10) and an optical spectrum analyzer (HP 70951B).

The threshold condition for a diode-end-pumped solid-state laser can be written as [11]

$$P_{th,i} = \frac{\ln\left(\frac{1}{R_i}\right) + L_i}{2l\eta_i f_i} \frac{h\nu_p}{\sigma_i \tau_i} \frac{1}{\iiint s_i(r,z) r_p(r,z) dv}$$
$$i = 0, 1 \tag{1}$$

where subscript i refers to the i transition wavelength, R_i is the reflectivity of the output mirror, L_i is the round-trip cavity loss, l is the length of the laser crystal, η_i is the quantum efficiency, f_i is the fraction of the ${}^4F_{3/2}$ population that resides in the Stark component used as the upper laser level, $h\nu_p$ is the pump photon energy, σ_i is the emission cross section, τ_i is the fluorescence lifetime at upper level, $s_i(r,z)$ is the normalized cavity mode intensity distribution, and $r_p(r,z)$ is the normalized pump intensity distribution in the active medium, $i = 0$ is for the 1064 nm, and $i = 1$ is for the 1074 nm.

The two wavelengths have the same upper ${}^4F_{3/2}$ laser level with close wavelengths in the same cavity; so, $s_0(r,z) = s_1(r,z)$, $r_0(r,z) = r_1(r,z)$, $L_0 = L_1$, and $\tau_0 = \tau_1$. Therefore, the threshold can be expressed as

$$P_{th,i} = C \frac{\ln\left(\frac{1}{R_i}\right) + L_i}{\eta_i \sigma_i f_i}$$
$$C = \frac{h\nu_p}{2l\tau_i} \frac{1}{\iiint s_i(r,z) r_p(r,z) dv}$$
$$i = 0, 1, \tag{2}$$

where C is an equal parameter for the two wavelengths.

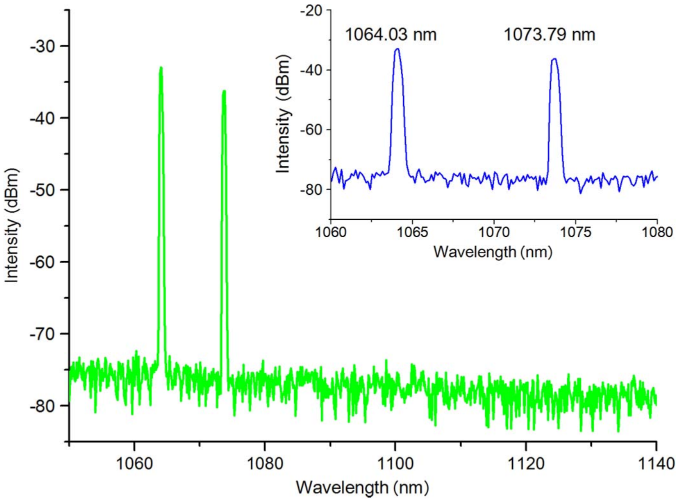

Fig. 3. Optical spectrum of the laser at pump power of 3.84 W. The inset shows the detailed spectrum of the laser.

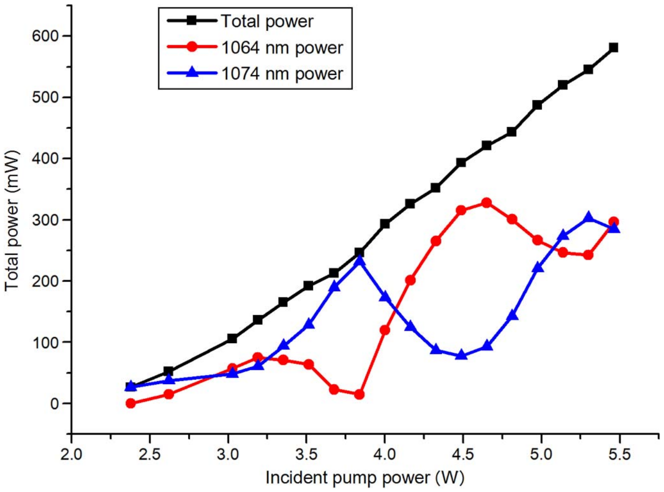

Fig. 4. Continuous output power properties of the Nd:YAG laser.

In order to obtain the 1064 nm and 1074 nm dual-wavelength laser, the thresholds for these two wavelengths should be about the same. For the Nd:YAG crystals [12], $\eta_0 = 808$ nm/1064 nm$=75.9\%$, $\eta_1 = 808$ nm/1074 nm$=74.5\%$, $\sigma_0 = 4.6 \times 10^{-19}$ cm^2, $\sigma_1 = 1.63 \times 10^{-19}$ cm^2, $f_0 = 40\%$, $f_1 = 60\%$, and L_0 is assumed to 0.01. In our experiment, $R_0 = 71.3\%$, $R_1 = 87\%$. Taking the above-known data into (2), we get, $P_{th,0} = 0.24C$, $P_{th,1} = 0.21C$. The thresholds of the two wavelengths are about the same and the threshold of the 1074 nm is lower than that of the 1064 nm, which indicate that the 1074 nm will lasing first. Following the same procedure, we could show that the threshold is $0.34C$ for 1112 nm, thus the 1112 nm is suppressed. Experiments showed that the FPF used as the output mirror can effectively balance the net gains of 1064 nm and 1074 nm to obtain a 1064 nm and 1074 nm dual-wavelength laser.

3. Results and Discussion

Fig. 3 shows the spectrum of the laser. The spectrum scanning range is from 1040 nm to 1140 nm. The results show that there are only two wavelengths in this range. The center wavelengths are 1064.03 nm and 1073.79 nm respectively.

Fig. 4 shows relationship between the output power and the incident pump power. The threshold pump power of the laser is 2.1 W. Spectrum measurement showed that the 1074 nm started lasing firstly. Then the 1064 nm appeared around 2.5 W pump power. According to the theoretical analysis in Section 2, the threshold pump powers are $0.21C$ and for the 1064 nm and 1074 nm respectively. Assume $0.21C$ equals 2.1 W, then $0.24C$ equals 2.4 W. Therefore, the experimental phenomena are in accordance with the theoretical analyzed results. The slope efficiency of the dual-wavelength laser is 18.8%. The maximum power obtained is 581 mW with pump power of 5.5 W. Thermal gradients with higher pump power may damage the crystal as the crystal is passively cooled. The output power could be higher with active cooling of the laser crystal.

As the two lasing wavelengths are closely located in spectrum and could not be spatially separated in our lab, a special filter (indicated in the right part of Fig. 2.) with partial transmissions at 1064 nm and 1074 nm is inserted between the RG830 filter and the power meter to obtain the powers of the respective wavelengths [8]. The filter is slightly tilted to avoid disturbance of the dual-wavelength laser by the reflected light. Assume the transmissions of the filter at 1064 nm and 1074 nm are T_{1064}, T_{1074} respectively, the total powers measured before and after the filter are P_a and P_b respectively, then there are the following relationships between powers of the 1064 nm part (P_{1064}) and the 1074 nm part (P_{1074}):

$$\begin{aligned} P_a &= P_{1064} + P_{1074} \\ P_b &= T_{1064}P_{1064} + T_{1074}P_{1074}. \end{aligned} \tag{3}$$

A filter with transmissions $T_{1064} = 10.8\%$, $T_{1074} = 35.2\%$ is used to obtain the powers of the respective wavelengths, and the results are plotted in Fig. 4. From Fig. 4, we can see that the powers of the respective wavelength did not change linearly with the incident pump power. The same phenomena are observed in other dual-wavelength lasers [9], [13], [14]. The culprit of the output powers oscillations of the respective wavelength is the gain competition between the lasing wavelengths. Temperature dependent stimulated emission cross sections may also lead to the variation in the ratio of 1064 nm to 1074 nm powers [15]. The temporal stability of the total power is better than 3% in one hour. The concrete mechanism leading to the power oscillations need to be further investigated.

The measured peak transmission wavelength of the FPF is slightly shifted from the wavelength anticipated by theory, because the layer thickness was controlled by deposition time. A more precise method to control the layer thickness in the filter deposition would result in smaller shift of the peak wavelength.

It is important in the design of the Fabry-Perot band-pass filter to obtain the desired 1064 nm and 1074 nm dual-wavelength laser. One main designing principle of the FPF is to control the ratio of the FWHM of the FPF and the spectral separation between the two lasing wavelengths (written as SS in the following discussion). Theoretically we have three kinds of choice, FWHM smaller than SS, FWHM equal SS, FWHM larger than SS. For our present 10 nm spectral separation, the former two choices will make the slope of the transmission curve too steep to gradually change the transmissions of the respective wavelengths, which is important to control the power ratio of the two lasing wavelengths. So, we choose FWHM (22 nm) larger than SS in this paper. The second main designing principle of the FPF is to locate the transition line with large stimulated emission cross section (1064 nm in this paper) close to the central wavelength (1052 nm in this paper) of the pass band. This principle can produce high transmission for the large cross section transition line, thus bring about high loss for that lasing wavelength and balance the net gain for the two lasing wavelengths. The third main designing principle of the FPF is to properly design the peak transmission. If the peak transmission is too high, the slope of transmission curve will be too steep to obtain a suitable transmission coefficient of the respective wavelength. If the peak transmission is too low, the slope of transmission curve will be too shallow to effectively suppress the strong emission wavelength. A properly designed FPF also should consider suppressing other undesired oscillations, such as 1112 nm in this paper.

TABLE 1

Typical dual-wavelength Nd:YAG laser

Category	Wavelengths (nm)	Corresponding transition	Obtaining method	Slope efficiency	References
Different up and lower Stark energy levers.	1061.5 1064	R1 to Y1 R2 to Y3	Temperature tuning		[6]
	946 1064	R1 to Z5 R2 to Y3	Coupled cavity Specially coated mirror	11.4% 11.3%	[7] [9]
	1074 1112	R1 to Y3 R2 to Y6	Specially coated mirror	23.6%	[8]
Same up Stark level, different lower energy level.	1052 1319	R2 to Y1 R2 to X1	Coupled cavity		[1]
	1064 1319	R2 to Y3 R2 to X1	Coupled cavity		[3]
	1116 1123	R1 to Y5 R1 to Y6	Etalon	9.2%	[5]
	1319 1338	R2 to X1 R2 to X3	Specially coated mirror	43.5%	[4]
Different up Stark level, same lower energy level.	1064 1074	R2 to Y3 R1 to Y3	Fabry-Perot band-pass filter	18.8%	This paper

Typical achieved dual-wavelength Nd:YAG lasers are summarized in Table 1. Compared with other dual-wavelength Nd:YAG lasers, the slope efficiency obtained in the paper is low. The authors believe that the slope efficiency could be higher after optimization of the laser design.

Compared with the coupled-cavity, etalon and specially coated mirror methods, the Fabry–Perot filter method presented in this paper has several advantages. Firstly, the selection of the oscillation wavelength is easy and precise. All you need is using a Fabry–Perot filter to balance the net gain of the two lasing wavelengths. Secondly, the wavelength separation between the two wavelengths is widely variable, which can be as small as 6 pm [16] and as large as a few tens of nm. Thirdly, the Fabry–Perot filter is easy to design and fabricate. The coating in this paper is composed of 21 layers. In comparison, the coating of the specially coated mirrors is usually around 50 layers to obtain the same transmission coefficients.

4. Conclusion

In summary, a 1064 nm and 1074 nm dual-wavelength Nd:YAG laser using a Fabry–Perot band-pass filter as output mirror is proposed and demonstrated. The dielectric Fabry–Perot filter is designed to balance the net gain of 1064 nm and 1074 nm to obtain a dual-wavelength laser. Simultaneous dual-wavelength lasing at 1064 nm and 1074 nm is successfully achieved with the pump power of 2.5 W. The threshold pump power of the laser is 2.1 W. The maximum output power of the dual-wavelength laser is 581 mW and the slope conversion efficiency is 18.8%. The design principles of the Fabry–Perot band-pass filter used as output mirror are discussed and the advantages of the method are summarized. Other features of the laser, such as the concrete mechanism leading to the power oscillations of single wavelength and the damage thresholds of the FPF, are now under investigation in our lab.

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