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High Efficiency and High Stability for SHG in a $Nd : YVO_4$ Laser with a KTP Intracavity and Q-Switching through Harmonic Modulation

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Abstract: In this paper, the stabilization and high efficiency of an unstable Second Harmonic Generation (SHG) of a $Nd : YVO_4$ laser with a KTP intracavity is carried out by using a passive Q-switching crystal and a parametric modulation method (harmonic modulation) is shown. The harmonic modulation was defined as $u_m(t) = A_m sin(2\pi f_m t)$, with modulation amplitude as $A_m(V_{pp})$, and modulation frequency as $f_m(Hz)$, applied to the pumping of the $Nd : YVO_4$—KTP laser to control the amplitude and frequency of the emission, thus stabilizing the dynamic states of this laser. The promising application of this green light source is materialized when such light is necessary for high-density optics, such as in the treatment materials industry or in some aesthetic applications.

Keywords: $Nd : YVO_4$ laser; Second Harmonic Generation; Q-switched lasers; frequency doubled

1. Introduction

Currently, one of the most widely used solid-state lasers in industrial applications, such as materials processing, cutting and welding, is the $Nd : YVO_4$ laser (yttrium orthovanadate crystal doped with neodymium) [1]. The $Nd : YVO_4$ is used due to its high absorption coefficient and its wide section of stimulated emission; in addition, it has a better performance as compared to a $Nd : YAG$ ($Y_2Al_5O_{12}$ aluminum oxide and itrium oxide doped with neodymium Nd+3) laser. However, thermal effects (thermal lens) are more significant in the $Nd : YVO_4$; so, it is necessary to monitor the glass temperature to keep it low [2–7]. Lasers doped with Nd^{+4}, such as Nd:YAG and $Nd : YVO_4$, usually emit radiation at a wavelength of 1064 nm, supported by a $KTiOPO_4$ crystal (potassium titanyl phosphate crystal or KTP). Inside the laser cavity, it is possible to double the frequency by converting the infrared light of 1064 nm into green light of 532 nm; this phenomenon is called Second Harmonic Generation (SHG) [8]. Due to the nonlinear coupling between modes in the SHG, the crystal leads to irregular fluctuations in the laser output, which is amplified by a Q factor of the laser cavity due to the presence of the amplifying laser [9], also known as the green problem. This irregular behavior has been studied in detail and attributed to the destabilization of the relaxation of the oscillations, which has always been present in this type of lasers due to the nonlinear coupling of the longitudinal modes [10–19].

There are several approaches in order to stabilize the green light generated by SHG in a solid-state laser. One of them is the use of external modulation, where low emission power is achieved by using nonlinear waves for SHG. This solution provides high conversion efficiency, and high power can be achieved by using flat waves [20]. In a $Nd : YVO_4$ laser, placement of the KTP crystal is fundamental

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to obtain green emission by folding the frequency. When the crystal is placed inside the cavity green radiation is emitted at high power, since the energy density of the radiation is higher inside the optical cavity. The green light intensity produced by the KTP crystal is proportional to the square of the fundamental wavelength intensity, but tends to be unstable. This instability is caused by the competition of modes in the cavity; if the KTP is placed outside the cavity, it is also possible to generate the second harmonic, and the emission in this case is stable, but with low power [21].

An approach to suppressing unwanted fluctuations is to control the injection current of the pump diode by means of electronic feedback. In 1992 [10], Rajarshi Roy et al. succeeded in stabilizing the output waveforms of the laser using a modification of the chaos control method proposed by Ott-Grebogy-Yorke (OGY) ([22]); this control technique is known as Occasional Proportional Feedback (OPF), and in other systems, such as CO_2 lasers, the method has been used to stabilize unstable periodic orbits [23]. A parametric modulation technique has been implemented by adding a sinusoidal signal to the system parameters in lasers made of erbium-doped fibers [24,25] to induce multistability and to stabilize the laser. The harmonic modulation technique consists in adding a periodic signal to the input of the system; in this case, it is a sinusoidal periodic signal to an accessible parameter of the laser system, to obtain a modulated parameter.

There is a method to increase the output power of a laser by modulating losses. This method is known as Q-switching, and it is divided into two techniques: active and passive Q-switching. In active Q-switching, losses are modulated by active elements, such as acousto-optic or electro-optic modulators; in passive Q-switching, losses are automatically modulated by a saturable absorber, and the pulse is generated when the energy stored in the medium reaches the appropiate level [26]. Normally, the average power of lasers in Q-switch operation is lower than the optical power of a continuous wave laser and the instabilities are reduced by placing a Q-switch crystal inside the cavity [27–31].

In this paper, an experimental study of a $Nd : YVO_4$ laser with a KTP crystal intracavity emitting at 1064 nm is shown. In such case, the KTP crystal produces a laser emission at 532 nm, which tends to be unstable and gives rise to the so-called "green problem" treated in recent years [10,11]. By applying controlled external modulation and using a passive Q-switching, it is possible to stabilize the emission and obtain a high conversion efficiency. The emission of the laser is analyzed based on the response in therms of optical power, optical spectra, frequency spectra and time series by using the local maxima and inter-spike-interval (ISI). This work focuses on stabilizing the green emission in frequency and pulse amplitude by adding harmonic modulation to the pumping current, where this modulation is applied by changing the amplitude and frequency. In Section 2 the experimental setup of a $Nd : YVO_4$ laser with a KTP crystal intracavity for second harmonic generation with external modulation is presented. Then, in Section 3, some results on stabilizing the frequency and amplitude of the SHG of the $Nd : YVO_4$ laser are shown. Finally, in Section 4, the results obtained and the conclusions are presented.

2. Preliminaries

There are a few methods to generate green light, but the best known is probably second harmonic generation. The green problem arises when the cavity generates not only the second harmonic, but also other frequencies due to the competition of longitudinal modes, which produce chaotic behavior[9]. The generation of those frequencies, as well as the generation of the second harmonic, are related to the polarization of the medium. This polarization occurs when an electric field is applied to the material as follows:

$$\vec{P} = \epsilon_0 \chi \vec{E}, \tag{1}$$

where ϵ_0 is the permitivity in the free space and χ is the linear susceptibility. If the electric field is small, the approximation is linear, but if the electric field is large, the best approximation is nonlinear; then, we can expand the equation of polarization in power series as:

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$$\begin{aligned}\vec{P} &= \epsilon_0\chi\vec{E} + \epsilon_0\chi^{(2)}\vec{E}^2 + \epsilon_0\chi^{(3)}\vec{E}^3 + \cdots + \epsilon_0\chi^{(n)}\vec{E}^n, \\ \vec{P} &= \vec{P}^{(1)} + \vec{P}^{(2)} + \vec{P}^{(3)} + \cdots + \vec{P}^{(n)},\end{aligned} \tag{2}$$

note that $\chi^{(2)}$, $\chi^{(3)}$, $\cdots$, $\chi^{(n)}$ are the nonlinear susceptibilities of second, third and n^{th}–order, respectively, and $P^{(n)}$ is the polarization of order n. Next, suppose an electromagnetic wave

$$\vec{E} = E_1e^{-\omega_1 t} + E_2e^{-\omega_2 t} + c.c.\,, \tag{3}$$

where ω_1 and ω_2 are frequencies, E_1 and E_2 are the involved amplitudes of the electromagnetic wave, while $c.c.$ represents a complex conjugate term. Substituting in the polarization of second order of Equation (2), the next equation is obtained:

$$\begin{aligned}\vec{P}^{(2)} &= \epsilon_0\chi^{(2)}(E_1e^{-i\omega_1 t} + E_2e^{-i\omega_2 t} + c.c.)^2, \\ \vec{P}^{(2)} &= \epsilon_0\chi^{(2)}(E_1e^{-i\omega_1 t} + E_2e^{-i\omega_2 t} + E_1^*e^{i\omega_1 t} + E_2^*e^{i\omega_2 t})^2, \\ \vec{P}^{(2)} &= 2\epsilon_0\chi^{(2)}(E_1E_1^* + E_2E_2^*) + \epsilon_0\chi^{(2)}(E_1E_1^*e^{-i2\omega_1 t} + E_2E_2^*e^{-i2\omega_2 t}) + \\ &\quad 2\epsilon_0\chi^{(2)}E_1^*E_2e^{-i(\omega_1+\omega_2)t} + 2\epsilon_0\chi^{(2)}E_1E_2^*e^{-i(\omega_1-\omega_2)t}.\end{aligned} \tag{4}$$

By analyzing equation (4), we can identify terms with different frequencies corresponding to the 4 non-linear effects of second order: Optical Rectification (OR), Second Harmonic Generation (SHG), Generation of Frequency Sum (GFS) and Generation of Difference Frequency (GDF):

$$\vec{P}^{(2)}_{OR} = 2\epsilon_0\chi^{(2)}(E_1E_1^* + E_2E_2^*), \tag{5}$$

$$\vec{P}^{(2)}_{SHG} = \epsilon_0\chi^{(2)}(E_1E_1^*e^{-i2\omega_1 t} + E_2E_2^*e^{-i2\omega_2 t}), \tag{6}$$

$$\vec{P}^{(2)}_{GFS} = 2\epsilon_0\chi^{(2)}E_1^*E_2e^{-i(\omega_1+\omega_2)t}, \tag{7}$$

$$\vec{P}^{(2)}_{GDF} = 2\epsilon_0\chi^{(2)}E_1E_2^*e^{-i(\omega_1-\omega_2)t}. \tag{8}$$

In the cavity of a laser, it is possible to generate other longitudinal modes, creating more frequency combinations and making the behavior more unstable [32]. The first time this phenomenon was observed in a laser was in 1961, when it was reported that in addition to the laser's natural wavelength (694.3 nm), a second harmonic (347.2 nm) had been generated [8]. With this finding the study of nonlinear optics and the use of SHG in different areas of science began [33,34].

3. Experimental Setup

In Figure 1, the scheme of the experimental arrangement of an $Nd:YVO_4$ laser with a KTP crystal intracavity for second harmonic generation is shown. As can be seen, the arrangement is the simplest in order to get the easiest way to generate the SHG. This experiment was carried out with a laser diode pumping at 808 nm (LD, Moduligth ML2020), a current source (Bk-Precision 1696) and a lens (L) with focal length f = 5 mm, which is used to focus the beam onto the $Nd:YVO_4$. The cavity consist of the $Nd:YVO_4$ crystal and a KTP intracavity glass, which have special coatings that work as reflecting surfaces at the wavelengths used (Figure 1), and at the output there are two beam splitters: BS1 (BS010), designed for wavelengths from 400 to 700 nm, and BS2 (BS011), is designed for wavelengths of 700 to 1100 nm. The resulting beam of BS1 is filtered by a bandpass filter (FL532-10, FG) at 532 nm, and the BS2 beam is filtered by a bandpass filter (FL1064-10, IRF) at 1064 nm. Such filtering affects photo-detectors PD1 and PD2, respectively, which convert the optical signal to an electrical one to be analyzed by the oscilloscope (DPO7104); the output of PD1 is also analyzed by a

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frequency spectrum analyzer (FSA Aeroflex). The unfiltered beam is introduced into an optical fiber to be analyzed in an optical spectrum analyzer (OSA MS9030A).

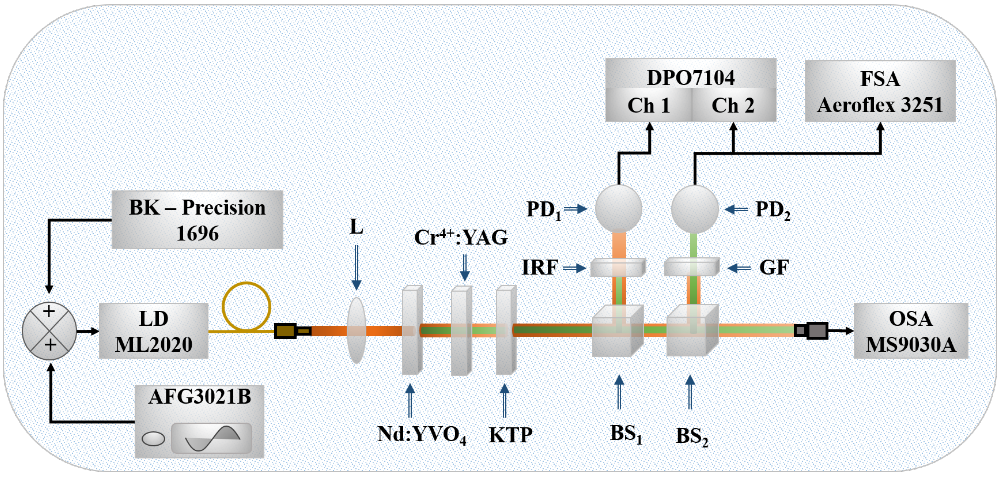

Figure 1. Schematic arrangement of the $Nd : YVO_4$-KTP laser with a KTP crystal intracavity for second harmonic generation and modulated by an external signal.

By carrying out the implementation of the experimental setup shown in Figure 1, it will be possible to know the unstable behavior that characterizes this type of laser and its output as a second harmonic. With this, we can analyze the original response of the $Nd : YVO_4$-KTP laser which will serve as a starting point before applying the harmonic modulation $A_m sin(2\pi f_m t)$ to the system.

In order to analyze the emission of the $Nd : YVO_4$-KTP laser with external modulation in the experimental setup shown in Figure 1, a sinusoidal modulation signal given by an arbitrary signal generator (AFG) is added to the pump current. With the AFG device, the pump current I_m is given as

$$I_m = I_0 + u_m(t), \tag{9}$$

where I_0 is the initial current parameter, and $u_m(t) = A_m sin(2\pi f_m t)$ is an external harmonic modulation, with A_m being the modulation amplitude (Vpp) and f_m (Hz) the modulation frequency. The control signal, with a suitable gain A_m and a frequency close to the desired limit cycle, must be able to eliminate coexisting states.

Using the same arrangement shown in Figure 1, it is possible to separate the green (532 nm) and infrared (1064 nm) emissions through the use of beam splitters (BS1 and BS2) at the output of the laser; then, we characterize the behavior of the laser when applying the modulation. The acquisition of data can be done through the use of the oscilloscope (temporal series), the optical spectrum analyzer (optical spectra), and the second harmonic (532 nm); the frequency spectrum can also be obtained, using the frequency spectra.

In order to select the best performance from the pump laser diode (LD), the voltage and current of the source were fixed as V = 7 V and I = 2.1 A, respectively, and modulation in frequency and amplitude was applied as 10 kHz $< f_m <$ 90 kHz in increments of 1 kHz, while amplitude was increased in steps of 1 Vpp within a range of 2 Vpp $< A_m <$ 20 Vpp. Figure 2a–e) shows the emission of LD at 808 nm for f_m = 60 kHz and A_m variable, and Figure 3a–e) shows the emission of the laser diode with A_m = 15 Vpp and variable f_m.

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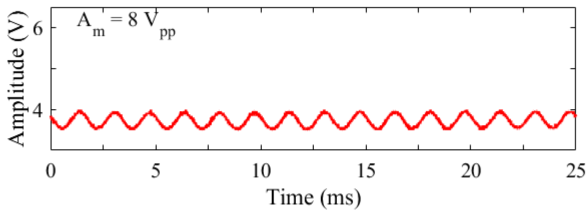
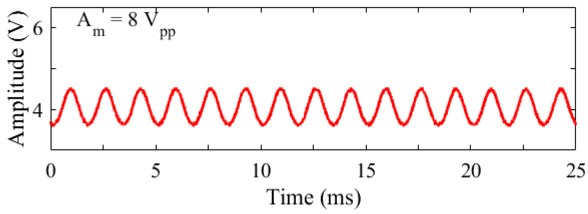


(a)



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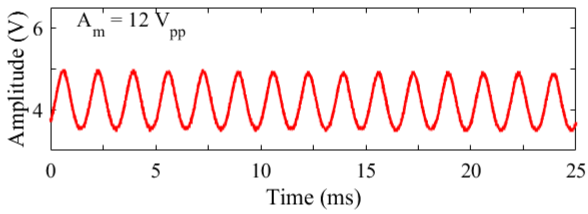

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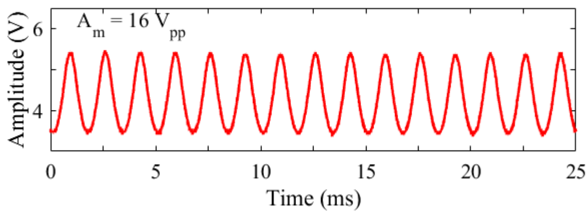

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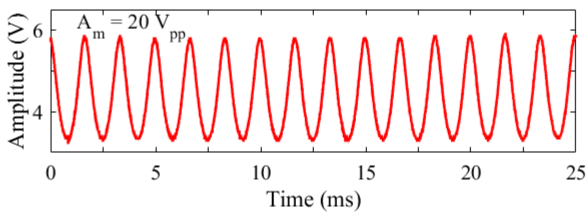

(e)

Figure 2. Pump laser diode emission by varying the harmonic modulation amplitude for a fixed frequency $f_m = 60kHz$ and modulation amplitude A_m: (**a**) 4 V, (**b**) 8 V, (**c**)12 V, (**d**) 16V, (**e**) 20 V.

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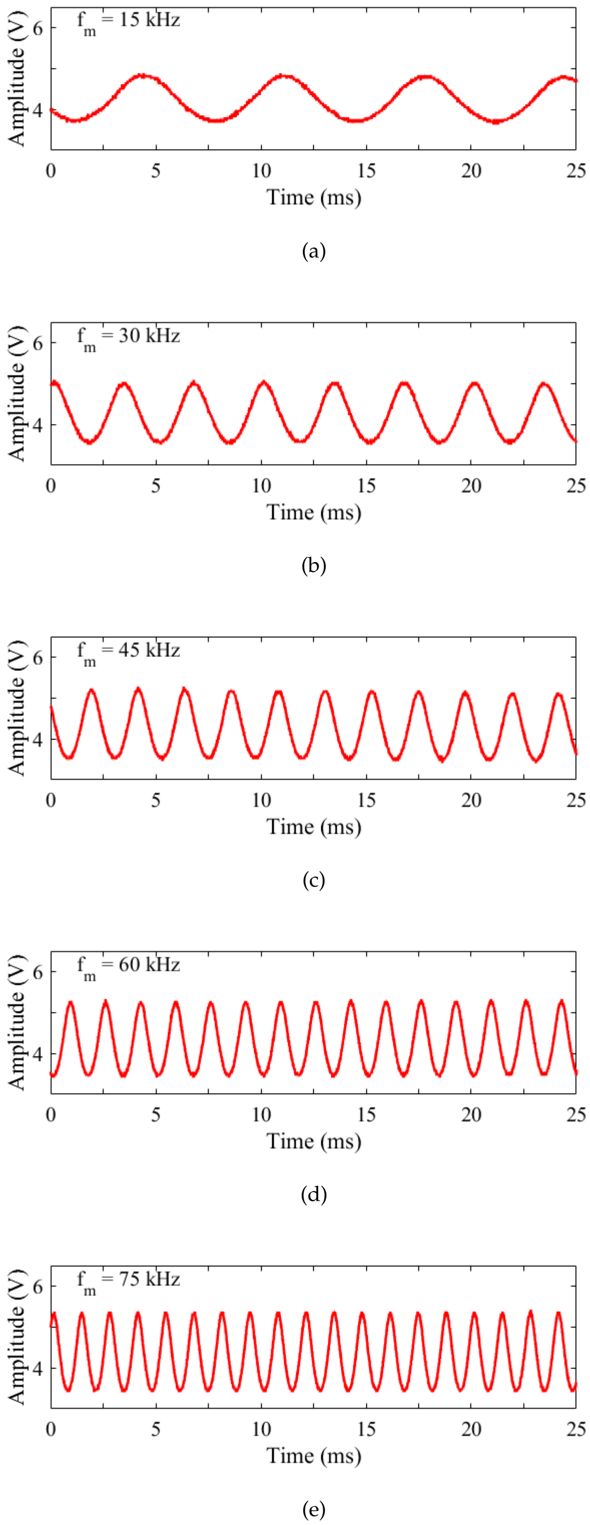

Figure 3. Laser diode emission by varying the harmonic modulation frequency and with fixed amplitude A_m=15 V and modulation frequency f_m: (**a**) 15 kHz, (**b**) 30 kHz, (**c**) 45 kHz, (**d**) 60 kHz, (**e**) 75 kHz.

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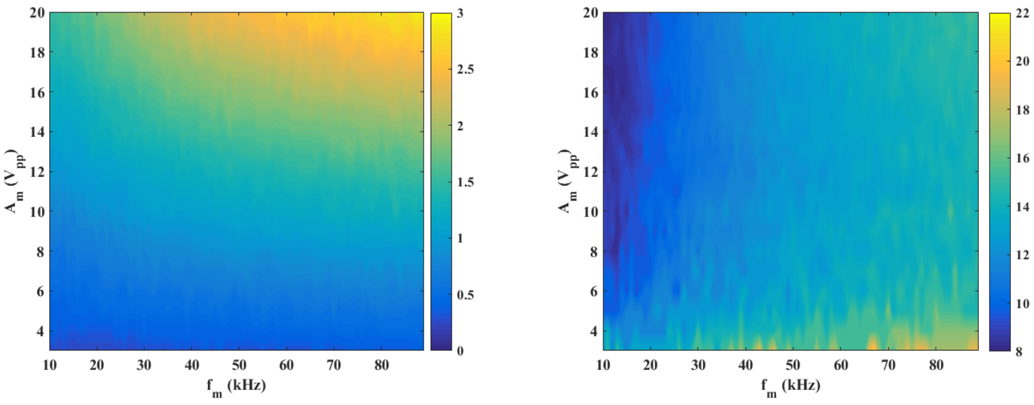
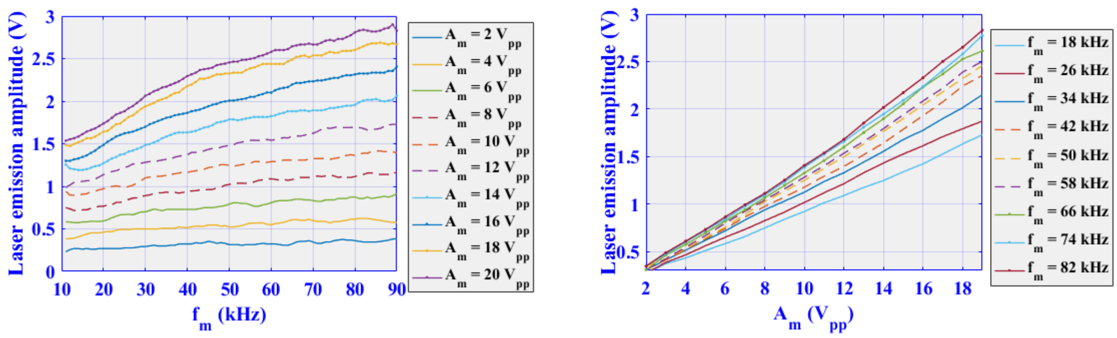


(a) (b)

Figure 4. (**a**) Peak-to-peak voltage map of the electric current of the DL emission when modulated with signal $u_m(t) = A_m \sin(2\pi f_m t)$. (**b**) Percentage relationship of the $\mathbf{V_{pp}}$ that presents the electrical intensity of the emission of the DL with respect to the modulation amplitude A_m (V_{pp}).

In Figure 4, we can observe that the peak-peak voltage (Vpp) of the emission increases by increasing f_m or A_m, but the intensity of the emission does not have the same amplitude to A_m, and only a percentage is observed; this relationship between the amplitude of the modulation and the amplitude of the emission is shown in Figure 5. The peak-to-peak voltage of the LD emission was calculated by varying modulation amplitude (Figure 5a) and modulation frequency (Figure 5b).



(a) (b)

Figure 5. Curves of V_{pp} of the emission of the LD varying (**a**) amplitude (A_m) y (**b**) frequency (f_m).

4. Results of the Stabilization in Frequency and Amplitude of SHG of the $Nd : YVO_4$

The stability of the intensity of the emission of the second harmonic in $Nd : YVO_4$-KTP lasers is known to be normally irregular; so, in this experiment, it was worked to stabilize the intensity of the emission and also to achieve greater conversion efficiency. The wavelength of the second harmonic (532nm) with respect to the emission at the fundamental wavelength (1064 nm). Passive Q-switching has been used to obtain an emission intensity with less stability, but they may present greater conversion efficiency of the laser power. It will be shown that with the harmonic modulation $u_m(t) = A_m \sin(2\pi f_m t)$, there is an emission intensity that has stability and greater conversion efficiency. In this section, the modulation parameters for amplitude (A_m) and frequency (f_m) are defined, for which the emission of the second harmonic has greater stability.

In order to know the behavior of the output power as a function of the pumping power, from the experimental arrangement shown in Figure 1, a sweep of 0 to 4.5W of optical pumping power was made, and the results can be seen in Figure 6, which shows the Nd:YVO_4 laser output, as a continuous

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wave and in Q-Switching mode at 1064 nm, as well as the power output as a continuous wave and in Q-Switching mode at 532 nm.

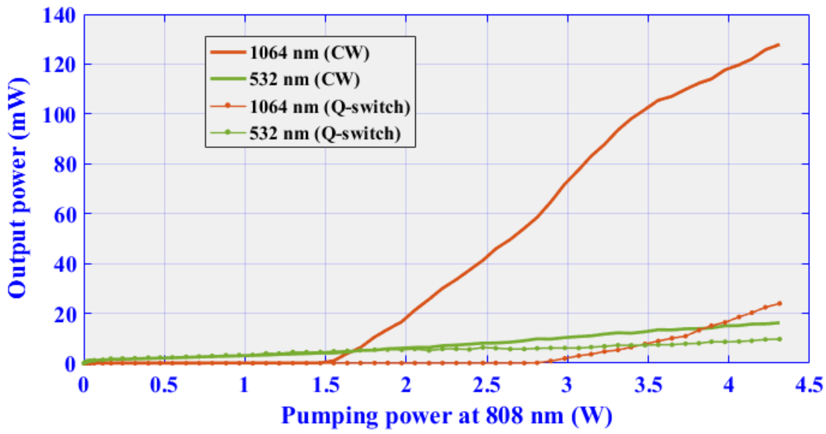

Figure 6. Power of the laser with KTP intra-cavity.

The intracavity conversion efficiency was found by relate the optical power at 532 nm to the optical power at 1064 nm. In Table 1, we can see that if the laser array was in the Q-switching mode, efficiency was 40%, higher than the results in previous works [30], whereas if the laser array was not in Q-switching mode, efficiency was only 12%.

	Q-Switch	Efficiency (%)
Intracavity	X	12.7
	✓	40.0

Table 1. Optical efficiency conversion with intra-cavity configuration at V = 7 V and I = 2.1 A.

Figure 7. shows the optical spectra amplitude at wavelength range 350 nm $< \lambda <$ 1300 nm of the laser emission $Nd:YVO_4$, with a modulation amplitude range 4 Vpp $< Am <$ 20 Vpp to know the behavior of current output when modulating the diode current. The characteristic wavelengths of 808 nm of the pump laser diode, 1064 nm. of the emission of $Nd:YVO_4$ and 532 nm. of the second harmonic when using the KTP are observed. The wavelength of 350 nm corresponds to the frequency sums phenomenon of the fundamental wavelengths 1064 nm and second harmonic (532 nm).

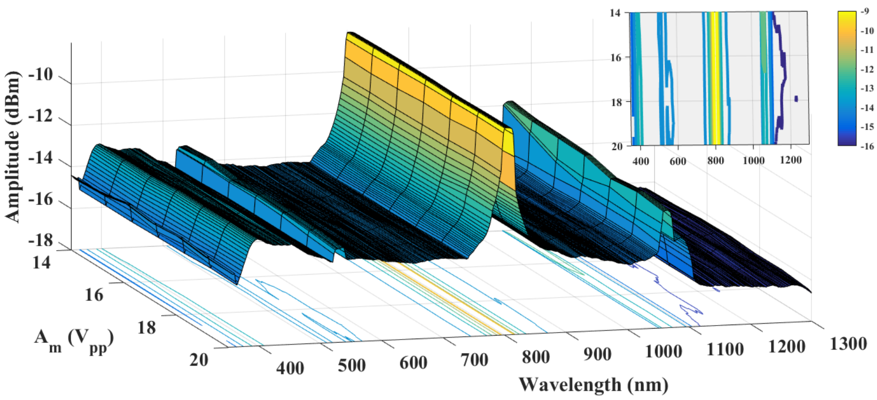

Figure 7. Surface of optical spectra.

Using the experimental arrangement for the laser configuration shown in Figure 1, it was found that the pulse frequency without modulation is $F_Q \approx$ 57 kHz; this is observed in Figure 8, where the parameters of the modulation signal were kept constant with voltage V = 7 V and current I = 2.1 A.

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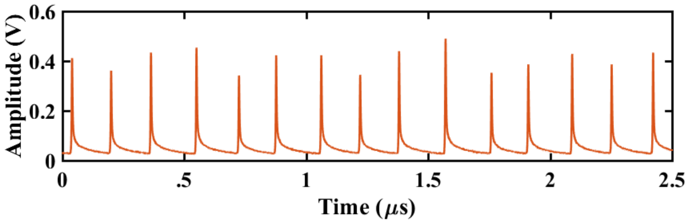
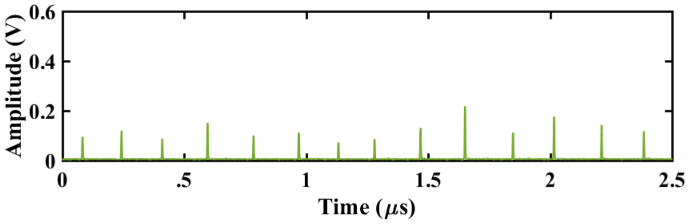


(a)



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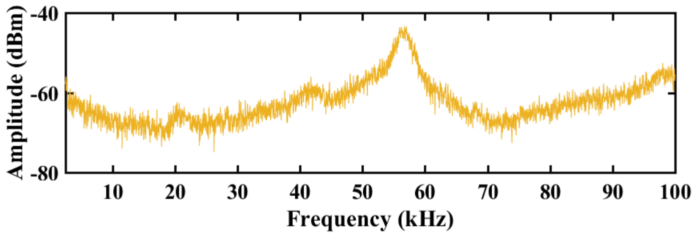

(c)

Figure 8. (**a**) Time series of the 1064 nm wavelength emission, (**b**) Time series of the wavelength radiation of 532 nm. (**c**) Spectrum frequency of the emission of 532 nm.

Using the experimental arrangement for the laser configuration shown in Figure 9, the frequency spectra of the $Nd : YVO_4$ laser emission were obtained by varying the modulation frequency 1 kHz $< f_m <$ 100 kHz while using a range of amplitude variation modulation of 4 Vpp$< A_m <$ 20 Vpp.

Figure 10 is a map in which the black areas represent the minimums of the standard deviation: Figure 10a) represents the standard deviation of the local maxima, Figure 10b) represents the standard deviation of the interspike-interval (ISI), and Figure 10c) represents the values of the parameters for which there are minimums of standard deviation of the ISI and of the local maxima of the emission at 532 nm.

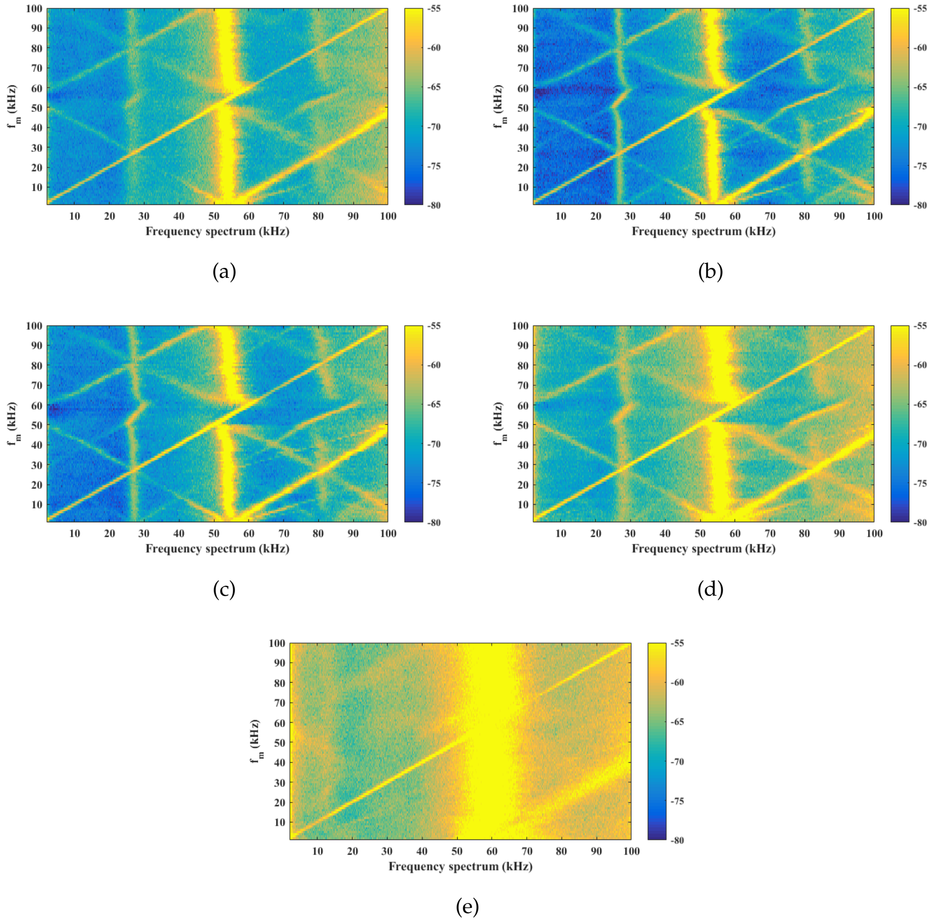

Figure 9. Frequency spectrum maps obtained by varying harmonic modulation frequency 1 kHz $< f_m <$ 100 kHz and modulation amplitude: (**a**) $A_m = 4$ Vpp, (**b**) $A_m = 8$ Vpp, (**c**) $A_m = 12$ Vpp, (**d**) $A_m = 16$ Vpp, (**e**) $A_m = 20$ Vpp.

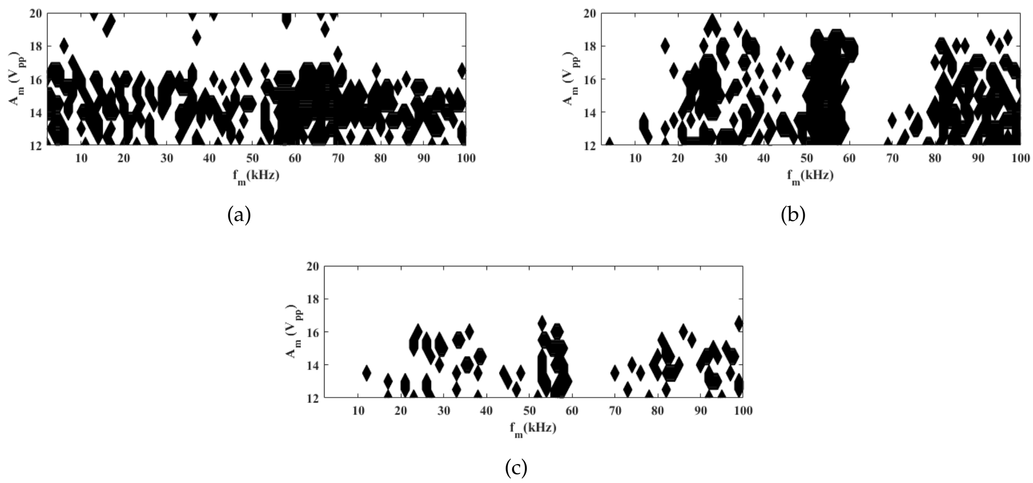

Figure 10. Stability zones for different amplitudes A_m and frequencies f_m.

5. Conclusions

The implementation of an intracavity $Nd:YVO_4$—KTP laser with passive Q—switching ($Cr4+:YAG$) was presented, using a harmonic modulation technique to stabilize the emission in amplitude and frequency of the laser. With respect to the optical power, it was found that the conversion efficiency between the fundamental wavelength 1064 nm and the wavelength of 532 nm, in pulsed emission (crystal for Q-switching) and using a saturable absorber ($Cr4+ : YAG$) intracavity, resulted in 40% conversion efficiency. Analyzing the time series of the laser emission when modulating signal $u_m(t) = A_m \sin(2\pi f_m t)$ is added to the pumping, the frequency looking is achieved at the dominant frequency range $45kHz < f_m < 60kHz$, for the amplitude $10V_{pp} < A_m < 20V_{pp}$; under this conditions the laser emission is stabilized in amplitude and frequency. The F_Q relaxation frequency of the Nd: YVO_4 laser was found using a modulation amplitude of $14V_{pp} < A_m < 16V_{pp}$ and a modulation frequency $fm = FQ = 57$ KHz. The best result appeared with the modulation parameters $A_m = 15V_{pp}$ and $f_m = 57kHz$, with which it was possible to stabilize the emission laser; those data were obtained from the calculation of the standard deviation of the local maxima and the ISI map. It can be said that in order to stabilize the emission of the $Nd : YVO_4$-KTP intracavity laser with passive Q-switching, a modulation frequency that is approximately equal to the oscillation frequency of the laser ($f_m = F_Q$), must be sought a harmonic resonance between the modulation frequency and the relaxation frequency of the laser, thus obtaining a stable emission of high efficiency.

Author Contributions: S.M.A.D.: Writing—Original Draft, Writing—Review & Editing, Methodology, Software, Validation, Data Curation, Visualization. J.H.G.L.: Writing—Review & Editing, Resources, Project administration. R.J.R.: Supervision, Funding acquisition, Writing—Review & Editing, Resources. V.A.: Writing—Review & Editing, Resources. J.L.E.M.: Writing—Review & Editing, Visualization, Conceptualization. G.H.C.: Writing—Original Draft, Writing - Review & Editing, Methodology, Software, Validation, Data Curation, Visualization, Project administration.

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