Grating cavity dual wavelength dye laser

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Abstract: We report simultaneous two wavelengths dye laser emission using Littman-Metcalf and Littrow cavity configurations with minimum cavity elements. Dual wavelength operation is obtained by laser operation in two optical paths inside the cavity, one of which uses reflection in the circulating dye cell. Styryl 14 laser dye operating in the 910 nm to 960 nm was used in a 15%:85% PC/EG solvent green pumped with a Q-switched doubled Nd^{3+}:YAG laser.

OCIS codes: (050.1950) Diffraction gratings; (140.2050) Dye lasers; (140.4780) Optical resonators

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1. Introduction

Recently there has been increased interest in laser systems emitting at two wavelengths [1-4] for many applications in different areas, one of them is the study of terahertz sources that has been active in the last few years. Terahertz waves, also known as far infrared, submillimeter waves or T-rays, cover the range of the electromagnetic spectrum between 0.1 and 10 THz (30 µm to 3 mm). The study in this range of the electromagnetic spectrum has been limited until recently due to lack of manmade sources. There are a few ways to obtain terahertz sources [5]: ultrashort laser pulses pumping semiconductor antennas [6], semiconductor quantum cascade lasers [7], direct multiplication of high frequency sources [8], nonlinear mixing of laser sources [9,10] or Raman shift of infrared gas lasers. Historically the first source in this wavelength range was obtained by nonlinear difference frequency generation of a ruby laser in quartz [11], but it was not until the development of time domain spectroscopy using ultrashort lasers pumping of semiconductor antennas [12] that an intense study in this region of the electromagnetic spectrum began.

In order to perform spectroscopy in the frequency domain a narrowband tunable light source at the wavelengths of interest is required. Of particular interest are the terahertz sources using nonlinear effects given the ability to synthesize and control in a direct way the frequency of the radiation resulting in tunable narrowband light. This has been obtained in using diode lasers or fiber lasers [13-21], unfortunately these produce low power terahertz radiation. Two wavelengths sources for terahertz generation must be preferable at long wavelengths such that the separation between wavelengths, in the order of terahertz, is easily achieved. The study of sources with emission in two wavelengths using as base dye lasers was studied extensively before terahertz sources were conceived and has begun to have a modest resurgence in recent years using a variety of configurations using multiple flow cells, gratings or mirrors [22-26]

In this paper we present, to the best of our knowledge, a two wavelengths laser using a ring grating cavity configuration, such as Littrow [27] and Littman-Metcalf [28], in a dye laser using total internal reflection on the circulating cell as a way to create the conditions to produce both wavelengths with minimum cavity elements.

2. Dye laser characterization

We studied the laser dye Styryl 14 (5,6-dichloro-2[8-(p-dimethylaminophenyl)-2,4-neopentylene-1,3,5,7-octatetraenyl]-3-ethylbenzothiazolium perchlorate; or Benzothiazolium, 5,6-dichloro-2-[[3-[4-[4-(dimethylamino)phenyl]-1,3-butadienyl]-5,5-dimethyl-2-cyclohexen-1-ylidene] methyl]-3-ethyl perchlorate; LDS 950 in the Exciton catalog) [29, 30]. The dye was dissolved in an 85% ethylene glycol (EG) and 15% propylene carbonate (PC) solution. It was optically pumped by a frequency doubled Nd^{3+}: YAG pulsed laser (Quantel Q-switched, 10 Hz, 6 ns) using a 50 mm potassium dihydrogen phosphate (KDP) crystal. This dye fluoresces in the vicinity of 940 nm.

The dye circulated uniformly on a 20 mm long quartz cell over a 2 mm aisle between a Teflon separator and the transparent front window used as pumping window (Radiant Dyes Laser Acc. GmbH, RDFC40). The pump beam was expanded to illuminate the length of the cell and focused using a cylindrical lens on a 15 mm width beam spot. We used both Littrow and Littman-Metcalf configurations. In both cases a gold coated 1200 lines/mm grating was used as tuning element.

Lasing action was achieved in Littrow configuration (Fig. 1) in which the cavity was formed between the first diffracted order of the grating back feed into the flow cell and the 10% Output Coupler (OC), stable due to the gain lens in the dye. The grating was placed at 150 mm from the end window of the circulating cell. The wavelength tunability was achieved by rotating the diffraction grating. Because of the grating diffracted angles, the grating was placed at a very acute angle. The output was monitored and measured from the flow cell in the opposite side of the diffraction grating.

The best laser output measured at 950 nm was obtained using Styryl 14 dye with a molar concentration of 8.4×10^{-4} M on the 15%-85% PC-EG solution. At this concentration we obtained a laser characteristic curve with a threshold of 1.06 mJ and a slope of 0.864 mJ/mJ. The largest conversion efficiency obtained was of 0.82% at 25 mJ pumping energy.

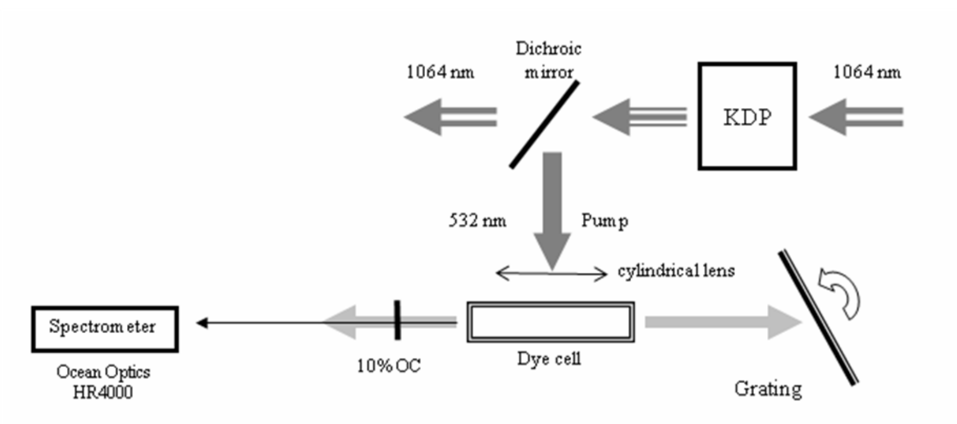


Fig. 1. Dye laser in Littrow configuration. Tuning is achieved by rotating the grating. OC: Output coupler

Lasing in the Littman-Metcalf configuration (Fig. 3) was obtained with the cavity formed between the first diffracted order of the grating retroreflected by a 100% dielectric mirror in the 950 nm region and a 10% Output Coupler (OC) placed at 100 mm from the cell. The distance between the retroreflecting mirror and the end of the cell was 200 mm. Again the grating was placed at an acute angle in order to achieve the retroreflection and the output was monitored and measured from the flow cell in the opposite side of the diffraction grating. The wavelength tunability was obtained rotating the 100% retroreflector mirror and the laser was stable due to the gain lensing in the gain medium.

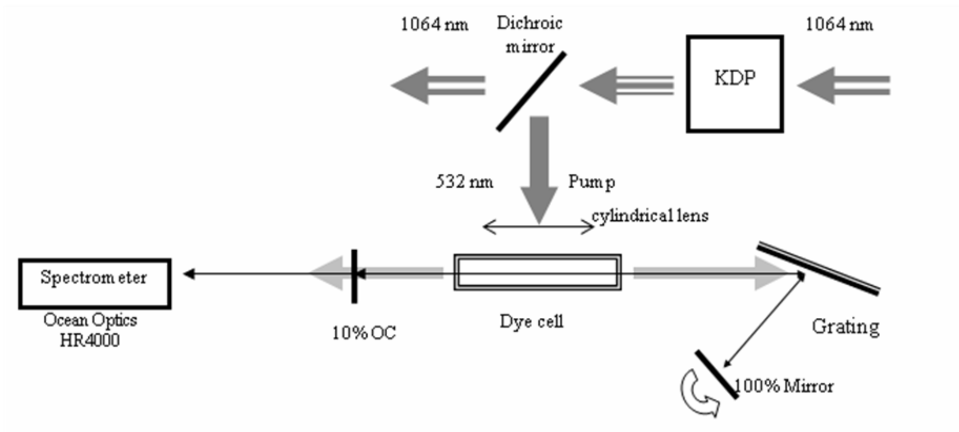


Fig. 2. Dye laser in Littman-Metcalf configuration. Tuning is achieved by rotating the 100% mirror. OC: Output coupler

Using the Littman-Metcalf configuration with Styryl 14 dye at the molar concentration mentioned above (8.4×10^{-4} M) we obtained laser output from 910 nm to 960 nm by rotating the tuning retroreflector mirror approximately four degrees (figure 4).

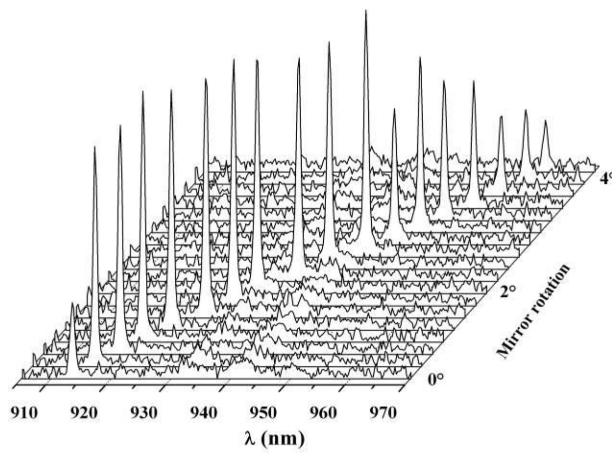
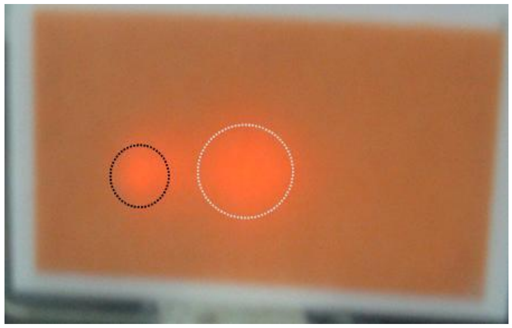


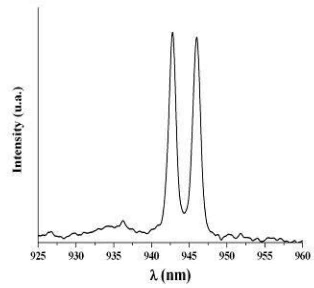
Figure 3. Wavelength tunability of the dye laser using Styryl 13 on a 15%:85% PC-EG solution with a 8.4×10^{-4} M concentration pumped by 532 nm 4 nsec pulses on Littman-Metcalf configuration.

3. Dual wavelength operation

As mentioned, contrary to the standard use of the Littrow and Littman-Metcalf configurations, we used the output coupler and observing side on the opposite side to the tuning grating while measuring the lasing capabilities response of the dye studied. As a consequence, we observed while lasing at some positions of the grating a double spot coming from the laser (Fig. 4a). Both spots departed from each other at approximately 1° to 5°. The initial assumption was that it was a reflection within the dye flow cell. When feeding the light into a spectrum analyzer using a collecting lens both spots were measured simultaneously and a double wavelength lasing operation was observed (Fig. 4b).



(a)



(b)

Fig. 4. (a) Double lasing spot observed on a fluorescent card placed 300 mm from the flow cell using Littman-Metcalf configuration. The left spot (black circle) is smaller than the right spot (white circle). (b) Spectrum obtained when both spots were measured simultaneously in the spectrum analyzer showing dual wavelength operation.

We considered different possibilities to explain the dual wavelength operation and obtained the explanation by examining the trajectories of the light inside the flow cell. Besides the standard grating cavity, there is a stable ring cavity tuned at different wavelengths explaining the dual wavelength operation. The ring trajectory is formed between the output coupler and the rear reflecting element returning using total internal reflection (TIR) on the interface between either the flowing dye and the quartz cell or the quartz cell and the air surrounding the cell. We were able to observe this behavior due to the distance between reflecting elements and the flow cell combined with the relatively long length of the cell.

Littrow configuration

We first turn our attention to the Littrow configuration [27], in which the grating is normally used as retroreflector on the first diffraction order for some specific wavelength (fig. 5). Longer wavelengths going to be diffracted to a larger angle and the opposite will occur for smaller wavelengths. The cavity is stable because the gain lensing occurring on the laser medium.

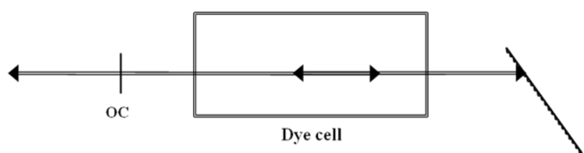


Fig 5. Dye laser cavity in Littrow configuration. OC: Output coupler.

As one of the reflectors closing the cavity is a diffraction grating, used as tuning element, the diffracting orders coming from a diffracting element are governed by the equation:

$$\Lambda\,(\sin\theta_i + \sin\theta_m) = m\lambda \tag{1}$$

where λ is the wavelength, Λ is the spatial frequency of the diffraction grating, θ_i is the incident angle with respect to the normal, and θ_m is the reflected angle with respect to the normal for the m'th order. For the first diffraction order the incident and diffracted angles are the same.

Now we observed the second cavity responsible for the dual wavelength operation. As mentioned it is formed between the output coupler and the rear reflecting element returning using total internal reflection (TIR) on the interface between either the flowing dye and the quartz cell or the quartz cell and the air surrounding the cell. In fig 6 an exaggerate version of the trajectory followed by the different beams is presented, in which the trajectory adjustment due to different refractive indices have been neglected for simplicity. There is only one wavelength which has the same incident and reflected angles in the output coupler and satisfies Eq. 1 simultaneously.

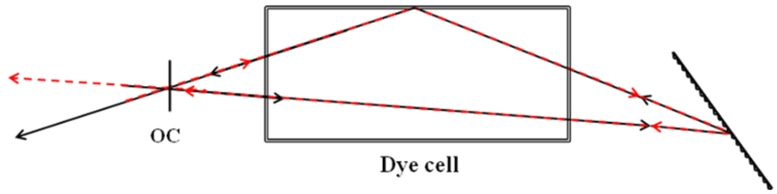


Fig 6. Ring cavity thorough the flow cell using TIR and the external reflecting elements.
OC: Output coupler

If we change the distance between the cell and the diffraction grating the angles needed to close the cavity necessarily change in order to accommodate the lasing action, therefore changing the wavelength of the ring cavity (figure 7).

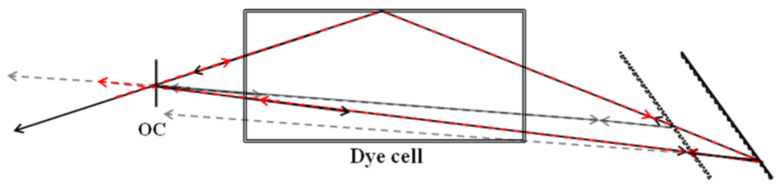


Fig 7. Ring cavity at different flow cell – diffraction grating distances. The angles required to form a stable ring cavity are different depending on the distance; in the figure the stable angles for the shortest distance (gray line) are not the same as if the grating is farther apart (red/black line), thus the angle selected by the grating is different. OC: Output coupler

This angle accommodation does not occur for the linear Littrow configuration (figure 5) which remains the same independent on the flow cell-grating distance. Therefore we can tune the wavelength separation between both wavelength by controlling the flow cell and the diffraction grating (d_{cm}), and tune the overall lasing system by rotating the grating. It has as a consequence that the new operating wavelength emerge the laser at a slightly different angle than the previous. The longer wavelength is achieved on the ring cavity. We can therefore have simultaneously two stable cavities which have lasing action in different volumes in the flow cell, therefore this can simultaneously lase in spite of having a homogeneously broadened gain medium as the dye (figure 8).

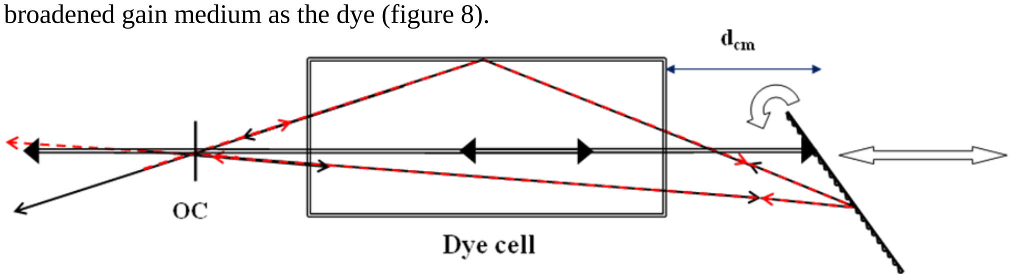


Fig. 8. Dual wavelength laser in Littrow configuration. Different wavelengths are obtained using the linear (double line) and ring (single line) trajectories depicted in the figure. Tuning is achieved by rotating the grating. Wavelength peak separation is achieved by controlling the separation (d_{cm}) between the grating and the flow cell. OC: Output coupler

Each wavelength departs from each other depending on the grating period and distances between the flow cell and the grating, explaining the double spot observed (figure 4a), which actually are three spots but two of them are close enough to be indistinguishable and appear as a larger spot. Both cavities cavities are stable due to gain lensing on the gain medium.

Littman-Metcalf configuration

In a slightly more elaborated way, the Littman-Metcalf configuration [28] has an equivalent behavior for the two wavelength operation. In this configuration the first diffracted order from the grating is retroreflected into the incident path using a mirror (figure 9).

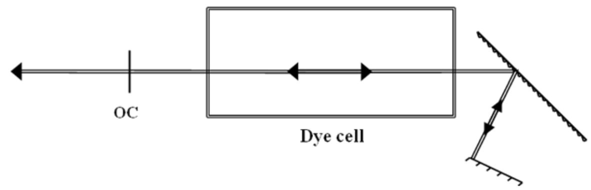


Fig 9. Dye laser cavity in Littman-Metcalf configuration. OC: Output coupler.

The second cavity responsible for the dual wavelength operation is once again formed between the output coupler and the rear reflecting element returning using total internal reflection (TIR) on the interface between either the flowing dye and the quartz cell or the quartz cell and the air surrounding the cell. In fig 10 an exaggerate version of the trajectory followed by the different beams is presented, in which the trajectory adjustment due to different refractive indices have been neglected for simplicity. There is only one wavelength which has the same incident and reflected angles in the output coupler and satisfies Eq. 1 simultaneously using the pivoting point in the reflecting mirror.

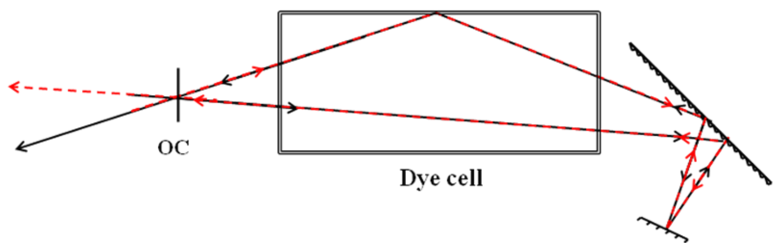


Fig 10. Ring cavity thorough the flow cell using TIR, the diffraction grating and a mirror reflecting the first diffracting order. OC: Output coupler

If we change the distance between the reflecting mirror and the diffraction grating, the angles needed to close the ring cavity necessarily change in order to accommodate the lasing action, therefore changing the wavelength of the ring cavity (figure 11). Similar behavior can be obtained by rotating the diffraction grating, but this will also change the wavelength of the linear Littman-Metcalf cavity, which is not a convenient option.

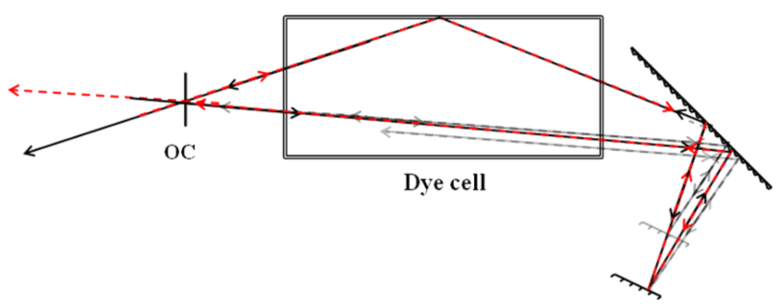


Fig 11. Ring cavity at different diffraction grating–mirror distances. The angles required to form a stable ring cavity are different depending on the distance; in the figure the stable angles for the shortest distance (gray line) are not the same as if the mirror is farther apart (red/black line), thus the angle selected by the grating is different. OC: Output coupler

Because we change the mirror–grating distance, leaving the grating unaltered, this angle accommodation does not occur for the linear Littman-Metcalf configuration (figure 9) which remains the same independent on the mirror-grating distance. Therefore, in this case we can tune the wavelength separation between both wavelength by controlling the mirror and the diffraction grating (d_{cm}), and tune the overall lasing system by rotating the grating. This change has also as a consequence that the new operating wavelength emerge the laser at a slightly different angle than the previous. Once again the longer wavelength is obtained in the ring cavity. We can therefore have simultaneously two stable cavities which have lasing action in different volumes in the flow cell, therefore this can simultaneously lase even when we use a homogeneously broadened gain medium as the dye (figure 12).

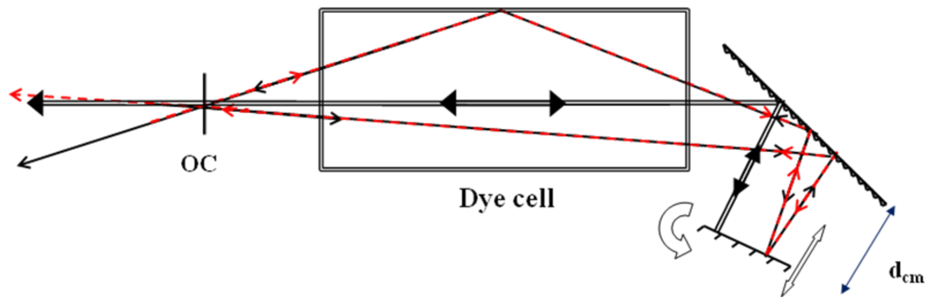


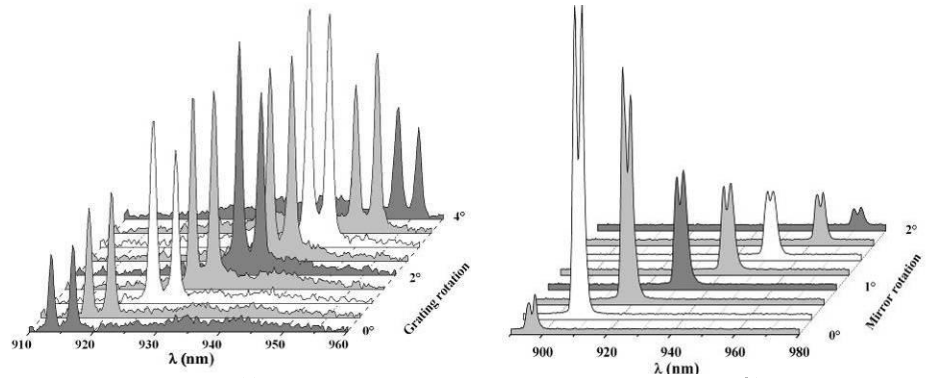
Fig. 12. Dual wavelength laser in Littman-Metcalf configuration. Different wavelengths are obtained using the trajectories depicted in the figure: linear (double line) and ring (continuous black/red line). Tuning is achieved by rotating the retroflecting mirror and the wavelength separation is controlled by the separation between the grating and retroreflecting mirror (d_{cm}).

As in the Littrow configuration, each wavelength departs from each other depending on the grating period, the mirror - grating distance and the separation between the grating and the retroreflecting mirror. In order to avoid competition from the Fabry-Perot cavity formed by the lateral windows in the flow cell, it is placed at an angle perpendicular to the cavity plane.

Therefore the dual wavelength operation in a dual cavity using traditional linear configuration and a ring cavity using total internal reflection using a gain medium in either Littrow or Littman-Metcalf configurations is possible based on the reflecting trajectories at different wavelengths, producing three exiting trajectories, two of which are close enough to be undistinguishable and appear as the larger spot in Fig. 4. The longer wavelength is achieved on the ring cavity, while the shortest is obtained in the traditional linear cavity. In order to have both cavities passing thorough the dye cell, the OC must present an small tilt to accommodate for both trajectories. We can foresee that a ring cavity using a dispersive element as a reflecting element will have similar dual wavelength operation.

4. Dual wavelength experimental observation

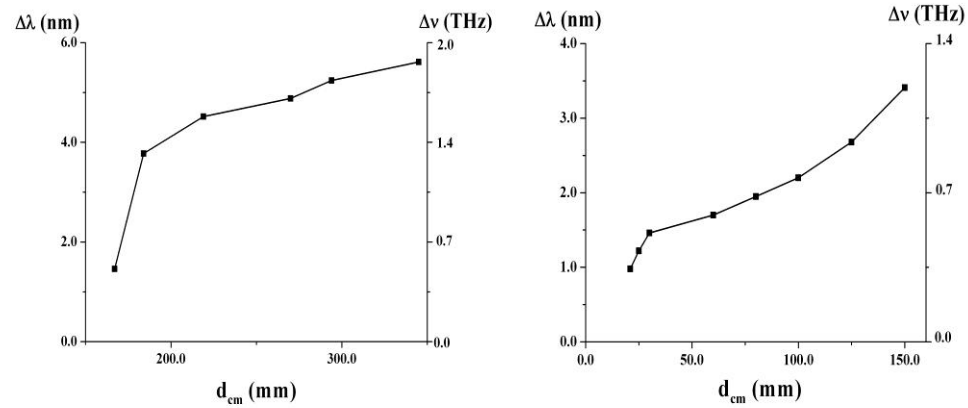
To perform a controlled observation of the dual wavelength operation of the laser we use the same experimental setup as described in the first section taking care of placing the dye flow cell at a small angle perpendicular to the ring cavity plane to avoid Fabry-Perot contribution of the lateral windows of the cell and placed the OC at a small angle with respect to the flow cell plane. The dual wavelength operation is tunable by rotating the grating in the Littrow configuration (Fig. 13a) or the retroreflecting mirror in the Littman-Metcalf (Fig. 13b) configuration. The dual wavelength tuning range on Littrow configuration, rotating the feedback grating close to 4°, was between 910 nm to 960 nm for the Littrow configuration. Rotating the retroreflecting mirror in the Littman-Metcalf configuration close to 2° the tunability achieved was from 900 nm to 970 nm. The characteristic curve for the dual wavelength operation present similar slope and threshold as the one wavelength experiments.



(a) (b)

Figure 13. Dual wavelength tunability of the dye laser using Styryl 14 on a 15%:85% PC-EG solution with a 8.4×10^{-4} M concentration pumped by 532 nm 4 nsec pulses on (a) Littrow and (b) Littman-Metcalf configurations.

Taking into account the 2 mm free opening in the flow cell between the quartz window and the Teflon separator for the 20 mm long flow cell allow angles between 0.5 and 2.5° for both configurations. Using Littrow configuration and changing the distance between the flow cell - diffraction grating (d_{cm}) between 20 mm and 150 mm, we observed a peak separation variation from 1.0 to 3.4 nm in wavelength or 0.35 to 1.2 THz, respectively (Fig 14b). At the same operating wavelength, using Littman-Metcalf configuration operating around 940 nm varying the distance between the grating and the retroreflecting mirror (d_{cm}) between 150 mm and 350 mm we measured a wavelength separation from 1.4 to 5.6 nm in wavelength or 0.5 to 1.9 THz in frequency, respectively (Fig 14b).



(a) (b)

Figure 14.Separation between wavelength in the dual wavelength operation with respect to the distance between the flow cell and the feedback element (d_{cm}) for the (a) Littrow and (b) Littman-Metcalf configurations.

Because both wavelengths travel in different volumetric space inside the circulating cell, the gain medium is not shared between the different paths and simultaneous lasing is achieved in spite of the homogenous broadening of the Styryl 14 dye gain medium in the PC/EG solvent. To verify that simultaneous lasing action occurs in both wavelengths simultaneously, we used a 3 mm x 3 mm x 3 mm c-cut Lithium Triborate (LBO) crystal to observe the harmonic signals in which we measured, using the aforementioned fast scanning monochromator, the second harmonic of each of the generated signals and the sum frequency generation between them (fig. 15). Sum frequency generation is observed only when both signals are simultaneously present, confirming simultaneous dual wavelength operation.

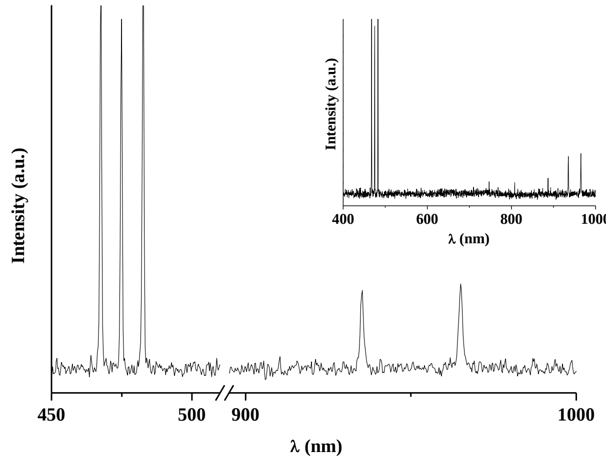


Fig.15. Dual wavelength lasing in Littrow configuration (λ_1 = 935.3 nm and λ_2=965.0 nm) and the signal through a LBO crystal exhibiting second harmonic (467.6 nm and 482.5 nm) and sum frequency generation (479.9 nm). The inset shows the complete wavelength scan in which a long pass filter was used to reduce the fundamental signals strength.

We monitor the tunability and wavelength separation controlled by the grating angle and the separation between the flow cell and the grating, respectively, for the Littrow configuration. For example we choose the sum frequency at 475 nm by changing the separation d_{cm} and rotating the grating to compensate the detuning (fig. 16).

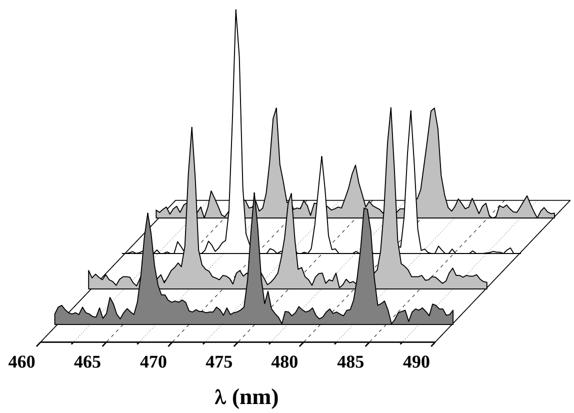


Fig.16. Wavelengths scan for the dual wavelength laser second harmonic and sum frequency when changing the flow cell-grating separation and tuning the wavelength to maintain the sum frequency at a fixed wavelength.

5. Conclusions

On this work we present a double wavelength dye laser using a grating cavity in Littrow and Littman-Metcalf configurations operating in the near infrared. The dual wavelength operation is achieved by means of two beam trajectories in the cavity configuration: traditional linear grating cavity and ring grating cavity. On the ring grating cavity the reflections occur on an output coupler, TIR in the flowing cell window and a diffraction grating retroreflector. As a consequence two independent wavelengths exit the laser at slightly different angle in which simultaneous operation was confirmed. The spectral separation among the two wavelengths can be controlled by varying the separation between the flow cell, the dispersing grating and the retroreflecting element.

In particular, pumping Styryl 14 laser dye in a 15%:85% PC-EG solution with 4 nsec pulses of 532 nm Nd^{3+}:YAG doubled laser we obtained single wavelength operation tunable between 910 nm to 970 nm using a 1200 lines/mm grating with threshold close to 1.0 mJ and slopes close to 0.9 mJ/mJ with an effective conversion efficiency of 0.82% at 25 mJ pumping energy. Under these conditions, on dual wavelength operation, varying the flow cell-retroreflecting element separation we obtained wavelength separation between 2 nm and 20 nm in either Littman-Metcalf or Littrow configurations, exiting at angles close to 2°.

Therefore we have obtained a dual wavelength laser system using minimum cavity elements: pumping source, flow cell with a dye laser, output coupler and a dispersive retroreflection element either a diffracting grating or a diffracting grating combined with a mirror. We can foresee that using the combined linear:TIR-ring cavities and any dispersive element as a reflecting element will have similar dual cavity and therefore independent laser dual wavelength operation. This type of system could be used as a THz source using difference frequency generation.

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