DISTRIBUTED FEEDBACK DYE LASER TUNING BY DIVERGENT PUMPING BEAMS

By

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A simple tuning method of distributed feedback dye lasers based on divergent beam pumping is presented. The tuning mechanism is described theoretically. The calculated and measured values of tuning sensitivity and maximum tuning are in good agreement. Continuous tuning of 5 Å was demonstrated experimentally.

Introduction

It has been shown recently that the N_2 laser pumped distributed feedback dye laser (DFDL) is capable of generating short transform-limited pulses. DFDL's are simple in construction, they produce stable, single picosecond pulses [1—3] without the use of expensive pulse selectors. Their operation range covers the visible and near UV part of the spectrum [4]. Amplification of the pulses by a few amplifier stages pumped by the same [5] N_2 laser is quite simple. It was found that the DFDL's have much lower amplified spontaneous emission (ASE) background level, and besides the efficiency and tuning range is about twice as large as that of the grating tuned lasers [6].

The pumping arrangements described in [4, 6, 7] allowed us to create a perfect pumping interference pattern even with superradiant (N_2, Cu-vapor, excimer *etc.*) lasers with low temporal and spatial coherence.

The pumping arrangement incorporating the quartz parallelepiped described in [4, 6] is very simple in construction and it can be easily aligned. However, it is a disadvantage that the simple tuning method, based on the rotation of mirrors [7], cannot be applied to this case.

In this paper, we are proposing a very simple tuning method, based on pumping the DFDL by divergent beams allowing a change of a few Å in the laser wavelength.

Theoretical considerations

DFDL's are usually pumped by an interference pattern created by two beams of very low divergency [9]. Thus the points of maximum intensities form parallel and equidistant planes. In this case the period of the interference pattern at the surface of the dye cell (and consequently, the lasing wavelength) is unchanged against the translations of the dye cell. A pumping interference pattern with tailored spatial dependent period allows a very straightforward tuning method, based on the shift of the dye cell. This principle was applied for tuning a DFDL in [10], where two slightly divergent pump beams were used to form the interference pattern. Similarly, we have also used divergent pump beams to pump the DFDL (Fig. 1). The pump source was a TEA-TE N_2 laser oscillator-amplifier system, similar to the one described in

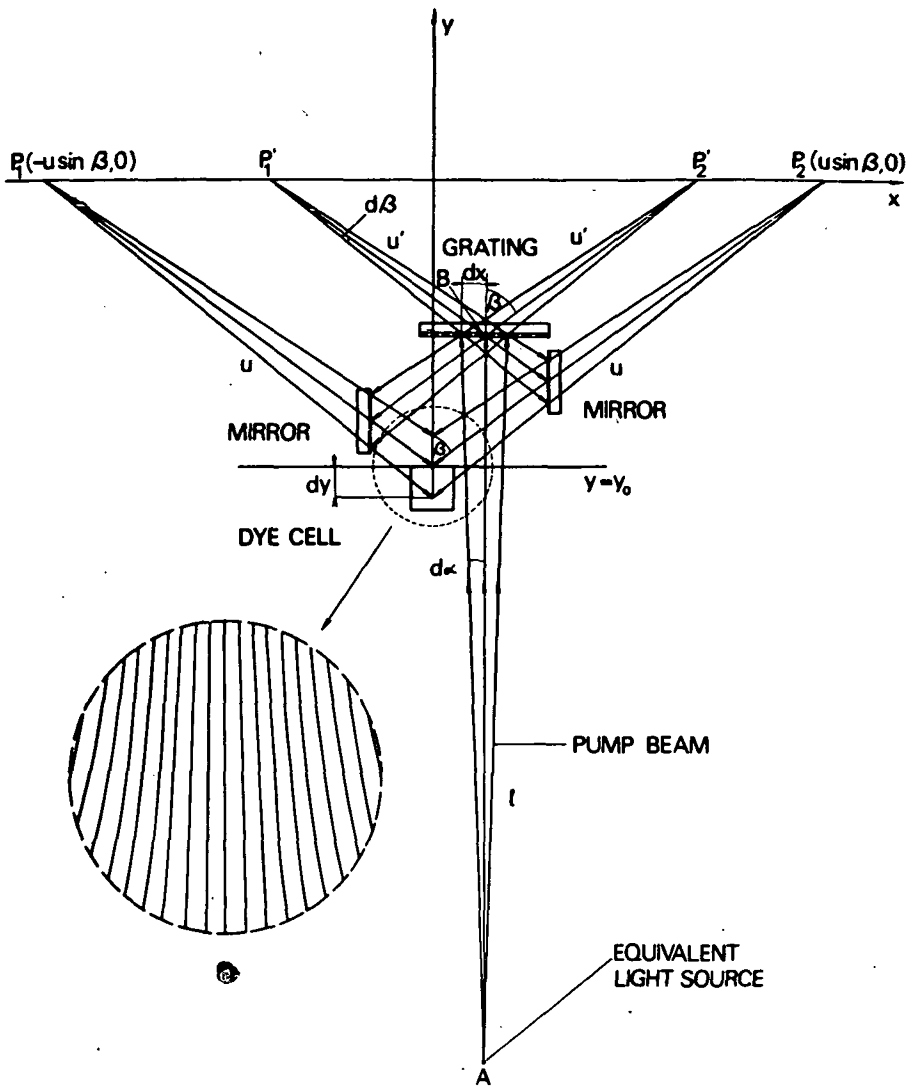

Fig. 1. The equivalent interference scheme of a DFDL pumped by divergent beams. P_1P_2 and A are the points where the two diffracted beams causing the interference and the pumping beam are emerging from, respectively.

[8] with a divergence of 0.4 mrad. The pump beam was sent through a telescope focussed almost to infinite. In this way, a pump beam was obtained which could be considered as to emerge from an equivalent point light source A. The position of point A was set by proper focussing the telescope. It can easily be shown (see Appendix 1) that the beams, diffracted by the grating, into the +1 and −1 orders are propagating as if they had emerged from points P_1' and P_2' respectively (see Fig. 1). The distance of P_1' and P_2' from the point B of the grating (u') can be calculated by $u'=l\cos^2\beta$ (see Appendix 1), where $l=\overline{AB}$, and β is the angle of diffraction. The beams, after being reflected form the two mirrors, produce the same interference as if they had emerged from points P_1 and P_2, thus the points of maximum intensities of the interference pattern form a set of hyperbolas. The distance of P_1 and P_2 from the dye cell (u) approximately equal to u' in our experiments. In Fig. 1, the co-ordinate system is chosen so that the co-ordinates of points P_1 and P_2 are $(-u\sin\beta, 0)$ and $(u\sin\beta, 0)$, respectively. Therefore, the equation of the curves of maximum intensities is:

$$\frac{x^2}{\left(\frac{n\lambda_p}{2}\right)^2}-\frac{y^2}{u^2\sin^2\beta-\left(\frac{n\lambda_p}{2}\right)^2}=1, \tag{1}$$

where: λ_p is the wavelength of pumping and, n is an integer (the order of the interference).

It is easy to show that the x co-ordinates of the maximum intensities at the surface of the dye cell ($y=y_0\equiv -u\cos\beta$) are given by

$$x_n=\pm\frac{n\lambda_p}{2\sin\beta}\sqrt{1+\frac{n^2\lambda_p^2\cos^2\beta}{4u^2\sin^2\beta-n^2\lambda_p^2}}. \tag{2}$$

The quasi-period of the DFDL structure is defined by

$$\Lambda=(x_{n+1}-x_n). \tag{3}$$

It can easily be shown that Λ varies along the axis of y. This effect can be used as a tuning method by shifting the active medium (or the grating) along axis y. There is also a small dependence of Λ on x which may spoil the periodicity of the DFDL structure. This effect can cause an unwanted line broadening. It can be proved easily by a geometrical consideration (Appendix 2) that the tangents of $y=y_0$ of the hyperbolas intersect at a point on axis y at a distance of $v=l\cos\beta$ from the $y=y_0$ line. Therefore the value of tuning sensitivity with respect to the shift of the dye cell:

$$\frac{d\Lambda}{\Lambda}=-\frac{dy}{l\cos\beta}. \tag{4}$$

Using the proportionality between Λ and the lasing wavelength (λ) we get:

$$\frac{d\lambda}{dy}=\frac{\lambda}{l\cos\beta}. \tag{5}$$

Equation (5) was verified experimentally. Fig. 2 shows the tuning sensitivity $\left(\frac{d\lambda}{dy}\right)$ versus the reciprocal distance of A from the grating $\left(\frac{1}{l}\right)$. The tuning sensitivity

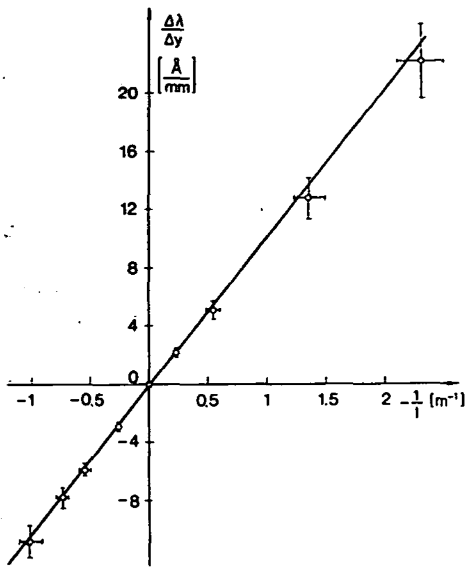

Fig. 2. The tuning sensitivity of DFDL based on the shift of the dye cell *versus* the reciprocal distance of A from the grating. The solid line is the theoretical curve, the points are the measured values.

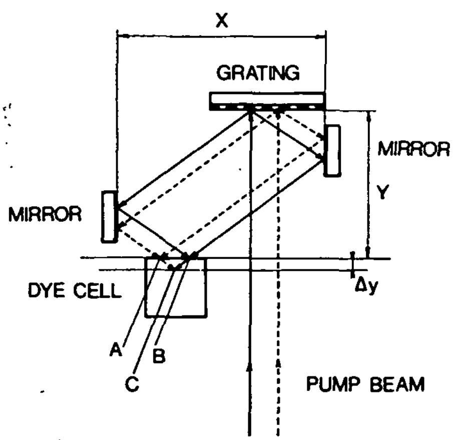

Fig. 3. The pumping arrangement produces an interference pattern with high visibility because the two beams coming from the same part of the pump beam (points A and B) interfere at the surface of the dye cell. When the dye cell is shifted (Δy), different parts of the beam interfere (at point C).

was determined by measuring the change in the wavelength and the corresponding shift of the grating. The wavelength tuning was measured by a Fabry—Perot interferometer (FSR=0.42 Å F=20). The value of l was calculated from the setting of the above mentioned telescope. The positive and negative values of l correspond to the divergent and convergent pump beams, respectively. In Fig. 2 the solid line is the theoretical curve, the points are the measured values. It can be seen that the agreement is very good.

Estimation of the tuning range

From equation (5), we obtain for the tuning range ($\Delta\lambda$) that

$$\Delta\lambda = \frac{\lambda}{l\cos\beta}\Delta y, \qquad (6)$$

where Δy is the possible maximum shift of the active medium.

Let us look for those physical effects which determine the maximum value of Δy and the minimum value of l. The pumping arrangement described in [7] has the advantage that, if the geometrical relation

$$\frac{Y}{X} = \sqrt{\left(\frac{d}{\lambda_p}\right)^2 - 1} \qquad (7)$$

holds (d is the grating constant), then two beams coming from the same part of the pump beam (see points A and B in Fig. 3) will interfere at the surface of the dye cell. Therefore there are no strict requirements for the spatial coherence of the pump beam. When the dye cell is shifted along axis y, the more distant parts of the pump beam produce interference (point C in Fig. 3). In this case, the visibility of the interference pattern decreases because of the finite spatial coherence of the N_2 laser beam. This effect limits the maximum value of Δy. Δy can be obtained by using the threshold characteristics of DFDL. The measured threshold of DFDL versus the shift of the grating is shown in Fig. 4. Parameter M is the magnification of the telescope placed between the DFDL and the N_2 laser system. In this experiment, the telescope was focussed to infinite. The intensity of pumping was varied by a variable liquid filter. In Fig. 4. it can be seen that by increasing Δy the threshold is also increased. Furthermore, the spatial coherence of pumping is proportional to the magnification of the telescope, because the curves can be transformed into each other by a magnification of $\frac{1}{M}$ along axis x. Earlier investigations have shown that, for pump pulse duration of 1.5 ns, the DFDL generates a single pulse only when the pump intensity does not exceed by more than 1.3 times the threshold pump intensity. This pump energy range of the single pulse generation was regarded as the maximum movement of the grating or different values of magnification M (see Fig. 4).

It was mentioned before that the periodic structure of the DFDL was not strictly equidistant for a finite value of l, *i.e.* in the middle of the excited volume was different from that at the ends (see (2) and (3)). Let us calculate the minimum value of l determined by the allowable maximum non-periodicity of the DFDL structure. Let the difference in Λ caused by the above-mentioned effect be denoted by $\Delta\Lambda$. Where:

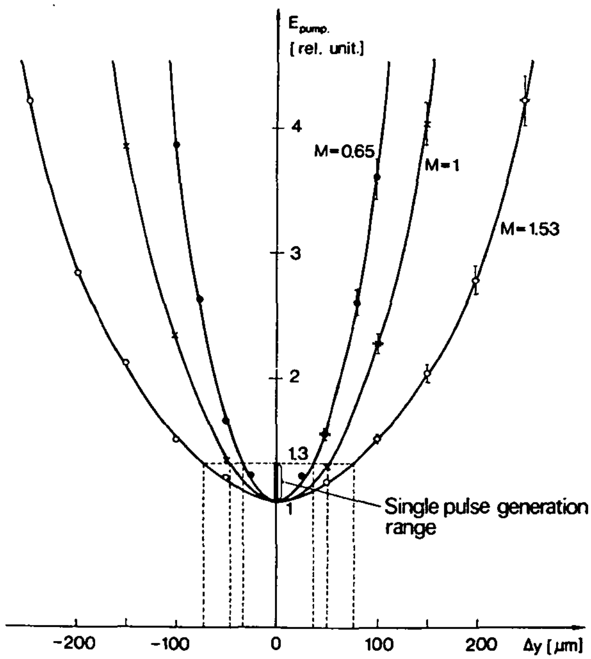

Fig. 4. The measured threshold pump energy *versus* the shift of the grating. Parameter M is the magnification of the telescope placed between the DFDL and the pumping N_2 laser system. All of the three curves are normalized at $x=0$ to unit.

Λ_0 is the quasi period belonging to $n=0$. Using equations (2) and (3), we get

$$\frac{\Lambda_n}{\Lambda_0}=\sqrt{1+\frac{n^2\lambda_p\cos^2\beta}{4l^2\cos^4\beta\sin^2\beta-n^2\lambda_p}}. \tag{8}$$

Using the $\lambda=d\sin\beta$ relation, and introducing the $\varphi=\frac{nd}{l}$ notation Eq. (8) becomes simpler:

$$\frac{\Lambda_n}{\Lambda_0}=\sqrt{1+\frac{\varphi^2\cos\beta}{4\cos^2\beta-\varphi^2}}. \tag{9}$$

Notice that φ is the half angle of the pump beam illuminating the DFDL consisting of $2n$ periods. Using the proportionality between Λ and λ from equation (7) and (8) for small values of φ, we can obtain

$$\frac{\Delta\lambda}{\lambda}\sim\frac{\varphi^2}{8\cos^2\beta}, \tag{10}$$

where $\Delta\lambda$ is the passive bandwidth caused by the non-periodicity of the DFDL structure. $\Delta\lambda$ is supposed not to exceed the expected bandwidth of the DFDL ($\Delta\lambda^*$). A DFDL operating under our experimental conditions (pump pulse duration is 1.6 ns) is expected to generate 40 ps long pulses, as described in [11]. The bandwidth corresponding to this pulse duration for transform limited pulses is approximately 0.1 Å. Using this value for $\Delta\lambda$, one can get for of $l=0.5$ m. With this value of l, and the highest magnification ($M=1.53$) of the telescope (see Fig. 4), a tuning range of 5 Å was achieved experimentally, as seen in Fig. 5. Fig. 5 shows the tuned DFDL output monitored by a Fabry-Perot interferometer (FSR= =0.84 Å, F=20). The curve was obtained from a signal of a Laser Photometer (Molectron LP 20), which formed the ratio of the power of the beam light having passed through the Fabry—Perot interferometer to the power of the beam entering the interferometer as the reference.

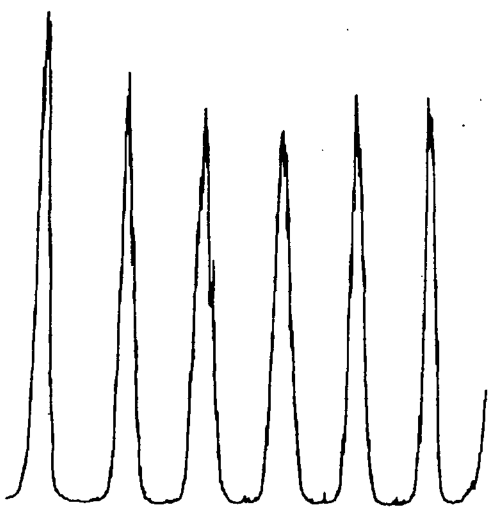

Fig. 5. The experimental tuning curve of the DFDL. Tuning was measured by a Fabry-Perot interferometer (FSR=0.84 Å, F=20) and a Laser Photometer (Molectron LP 20).

The tuning method described above is based on dependence of Λ on y. Since the size of the active volume in this direction is in the order of hundreths of microns, the change in Λ can be considerable so as to lead to the broadening of the linewidth.

This effect can be avoided, if

$$(\Delta\lambda)^* < \left(\frac{d\lambda}{dy}\right)^* \cdot h, \tag{11}$$

where $\frac{d\lambda^*}{dy}$ is the dependence of λ on y inside the excited volume $\frac{d\lambda^*}{dy} = \frac{d\lambda}{dy} \frac{\cos\beta}{\cos\alpha} \frac{1}{n}$ (see Appendix 3), and h is the penetration depth of pumping. Condition (11) can be fulfilled by increasing the concentration of the dye solution, but this is limited by diffraction losses. Under our experimental conditions the the $6 \cdot 10^{-3}$ M Rhodamine 6G solution provided the best performance. It should be mentioned that by increasing the value of φ not only the bandwidth of the DFDL is increased, but also the divergence of the DFDL. This effect is caused dy the non-parallelism of the interference lines. The value of the divergence can be estimated knowing the rise of the tangents of the hyperbolas and taking into consideration the law of their refraction (Appendix 3).

We have observed an increase in the divergence of the DFDL experimentally, as well.

Conclusion

We have described theoretically and studied experimentally a tuning method based on pumping the DFDL by divergent beams. The method is capable of a tuning of a few Å, and can be applied also when the pump arrangement incorporating a quartz parallelepiped is used [4, 6]. It is very likely that the reason for the tuning effect observed in [7] is the same as described above.

Appendix

1. From the grating equation, we can obtain:

$$\cos\alpha\, d\alpha = \cos\beta\, d\beta, \tag{A1}$$

where: α is the angle of incidence, (in our case $\alpha=0$), and β is the angle of diffraction. It can be read from Fig. 1 that

$$d\alpha = \frac{dx}{l}, \tag{A2}$$

and

$$d\beta = \frac{dx\cos\beta}{u'}, \tag{A3}$$

Therefore starting from (A1)—(A3)

$$u' = l\cos^2\beta \tag{A4}$$

It can easily be calculated by simple geometrical considerations that

$$u = u' + X^2 + Y^2, \tag{A5}$$

2. Let point P be an arbitrary point of the excited volume belonging to the optical path difference of $n\lambda_p$ (Fig. 5). It is well known from geometry that the tangent of the hyperbolic curve at P is the bisector of $\overline{PP_1}$ and $\overline{PP_2}$. Applying the sine-formula for the triangle of P_1P_2P, we get for a small value of $d\beta$ that

$$\frac{\sin(\gamma+d\beta)}{\sin(\gamma-d\beta)}=\frac{u+\frac{n\lambda_p}{2}}{u-\frac{n\lambda_p}{2}}. \tag{A6}$$

In our experiments $\frac{n\lambda_p}{2} \ll u$. In this case, (A6) is simplified to

$$d\beta=\frac{n\lambda_p \operatorname{ctg}\beta}{2u}. \tag{A7}$$

It can be read from Fig. 5 that

$$d\beta=\frac{\overline{OP}}{v}=\frac{n\lambda_p}{2v\sin\beta}. \tag{A8}$$

Comparing (A7) and (A8) we can obtain:

$$v=\frac{u}{\cos\beta}=l\cos\beta. \tag{A9}$$

Since v is independent of n, it means that all the tangents of a hyperbola intersect at the same point C.

3. Let us look for the refraction law of the maximum intensity curves of the interference pattern formed by two beams intersecting at an angle of 2β, when they

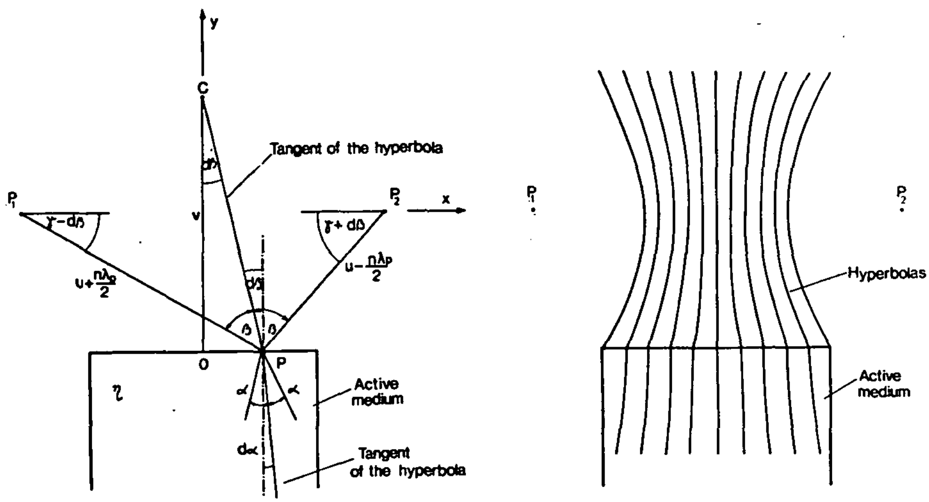

Fig. 6. Geometry for the calculation of tangents of the hyperbolas and their law of refraction.

are at the surface of a medium with a refractive index of η. Let $d\beta$ be the angle between the tangent of the maximum intensity curve ($\overline{PC}$) and the normal of the surface (indicated by a broken line in Fig. 6). In terms of the Snell's law we can obtain:

$$d\alpha = \frac{1}{2}\left\{\arcsin\frac{\sin(\beta+d\beta)}{\eta} - \arcsin\frac{\sin(\beta-d\beta)}{\eta}\right\}.$$

Assuming a low value for $d\beta$:

$$d\alpha \approx \frac{\cos\beta}{\cos\alpha}\frac{1}{\eta}\,d\beta,$$

which can be regarded as the refraction law of the interference fringes.

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ПЕРЕСТРАИВАНИЕ РОС ЛАЗЕРОВ, ВОЗБУЖДЕННЫХ РАСХОДЯЩИМ ПУЧКОМ

Ж. Бор, Ш. Сатмари, Г. Сабо и Б. Рац

Описан способ простого перестраивания по длине волн РОС лазеров, возбужденных расходящим пучком. Теоретически изучен способ перестраивания. Расчетные и экспериментальные данные характеристики перестраивания и максимальной области перестраивания находятся в хорошей соответствии. Экспериментально продемонстрировано непрерывное перестраивание в области 5 ангстрэмов.