SCISPACE
formerly Typeset

Open access • Journal Article • DOI:10.1364/AO.34.007670

Bessel-beam-pumped tunable distributed-feedback laser. — Source link

Steffen Klewitz, Frank Brinkmann, Stephan Herminghaus, Paul Leiderer

Institutions: University of Konstanz, Max Planck Society

Published on: 20 Nov 1995 - Applied Optics (Optical Society of America)

Topics: Bessel beam, Laser beam quality, Tunable laser, Beam parameter product and Distributed feedback laser

Related papers:

- Diffraction-free beams.
- Exact solutions for nondiffracting beams. I. The scalar theory
- Continuous-wave dual-wavelength operation of a distributed feedback laser diode with an external cavity using a volume Bragg grating
- Distributed feedback (dfb) brillouin fiber lasers
- Nonlinear optics of Bessel beams

Share this paper:

View more about this paper here: https://typeset.io/papers/bessel-beam-pumped-tunable-distributed-feedback-laser-42x0b06ybd

First publ. in: Applied Optics 34 (1995), 33, pp. 7670-7673

Bessel-beam-pumped tunable distributed-feedback laser

Steffen Klewitz, Frank Brinkmann, Stephan Herminghaus, and Paul Leiderer

A distributed-feedback (DFB) dye laser that is pumped by a standing Bessel-beam wave is constructed. Because of the long line focus of the Bessel beam, the laser medium is pumped in only a very thin filament (a few micrometers) along the optical axis. At the same time, longitudinal-mode selection is achieved because of the DFB effect. It is demonstrated that when the effective wavelength of the Bessel pump beam is varied, the Bragg wavelength for DFB is altered, and as a result the output wavelength can be tuned.

1. Introduction

The basic requirements for extended tuning of a laser is having a broadband gain of the laser medium and having a method of selecting one frequency out of this spectral range. One concept for narrow-band wavelength selection is to use distributed-feedback (DFB) in the laser medium. This method is based on periodic modulation of the refractive index or gain in the optical path. Laser dyes are known to provide a broad band of high gain, so the combination of DFB and a dye as the active medium yields widely tunable lasers and has been used extensively.[1–6]

The periodic modulation of refractive index or gain in DFB dye lasers is usually achieved by means of an interference pattern in the pumping-light field. The spatially periodic modulation of the pump intensity gives rise to spectral selection of the longitudinal modes because of the wavelength selectivity of the Bragg effect.[7] The dispersion relation is thereby modified as well, leading eventually to stop bands in the optical field of laser emission.[8] In the usual (transverse) pumping schemes, the pump beam is split into two beams, which are projected into the dye in order to yield the desired interference pattern.

If one wants to achieve transverse-mode selection at the same time, a thin, long filament of intense light is necessary. If the pumped volume is a cylinder with a large ratio of length to diameter, zero-order modes reach threshold first because the mode intensity close to the axis increases for a decreasing order of the modes. From a long interaction region one can also expect a lower threshold and a smaller linewidth. Commonly a cylindrical lens is used to obtain a pumping field that is elongated in the direction of the desired laser beam and focused in its normal direction.[1] But the focus of a cylindrical lens is far from being an ideal, cylindrically symmetric pump volume. It is the purpose of the present paper to demonstrate that all three demands, maximum length of the intense filament, tunability of the periodic longitudinal intensity modulation, and a narrow cylindrically symmetric pumped area, can be easily achieved by using a standing Bessel wave as the pump beam.

The authors are with the Universität Konstanz, Postfach 5560, D-78434 Konstanz, Germany.

Received 19 January 1995; revised manuscript received 14 July 1995.

0003-6935/95/337670-04$06.00/0.

2. Bessel Pump Beam

A Bessel beam may be viewed as consisting of a set of plane waves whose **k** vectors include a given angle γ with the optical axis. Hence the **k** vectors are lying on a cone. These waves mutually intersect each other, thereby forming an interference pattern. The transverse-intensity profile in the radial direction is then given by a zero-order Bessel function of the first kind.[9] We define γ as the steepness of the Bessel beam [see Fig. (1)]. An important fact is that the intense inner spot of the Bessel beam does not change its width while it is propagating along the central axis. Hence this long line focus can be considered to be a nondiffracting beam.

Since Durnin[9,10] pointed out the existence of solutions of the wave equation that provide diffraction-free beams, various generation schemes and applica-

Konstanzer Online-Publikations-System (KOPS)
URL: http://www.ub.uni-konstanz.de/kops/volltexte/2007/3030/
URN: http://nbn-resolving.de/urn:nbn:de:bsz:352-opus-30300

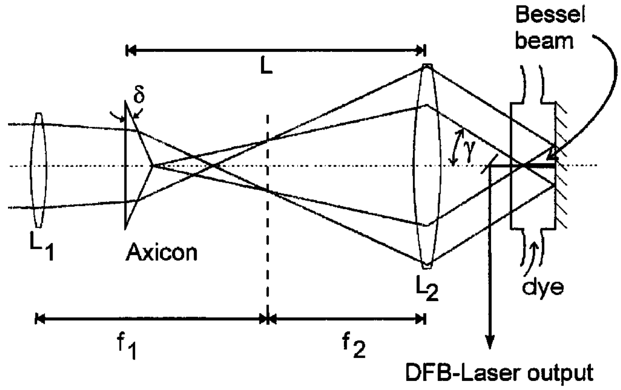

Fig. 1. Experimental setup: the expanded beam from a pulsed Nd:YAG laser is sent into an optical setup that allows us to vary the steepness γ of the Bessel beam. A standing Bessel wave is formed in the dye by reflection from the mirror at the rear side of the cuvette and leads to laser output. L_1, L_2, lenses; L, distance between the Axicon and L_2; δ, axicon basis angle; f_1, f_2, focal lengths of lenses L_1 and L_2, respectively.

tions have been found.[11–13] A commonly neglected fact in the treatment of Bessel beams is that under certain circumstances, the tunable effective wavelength $\lambda = \lambda_0/\cos(\gamma)$ determines the results of the experiment. Together with the high intensity and the long interaction length of the line focus, the tunability of the effective wavelength can be a powerful tool in nonlinear optics. Phase matching of the second-harmonic generation of a Bessel beam in a KDP crystal at unusual angles has already been demonstrated.[14]

Bessel beams therefore are also interesting for the design of DFB lasers. For generation of the Bessel beam we used an axicon,[15,16] which was a glass cone in our case. Axicons have already been suggested for effective pumping schemes of some lasers,[17] mainly because of the resulting high radial uniformity of the pump beam, which shows a maximum of intensity along the axis, even in an absorbing dye. Axicon laser pumping is an established method and was carried out in several studies.[18,19] But the tunability of the effective wavelength of the Bessel pump beam that was obtained has not used up to now. If one builds up a standing Bessel wave pattern by reflecting a Bessel beam into itself, a long line focus of intense spatially modulated light with a diameter of some micrometers that can be used to pump a laser medium is formed. Pumped with light of wavelength λ_0, the wavelength of this standing Bessel beam is

$$\lambda = \frac{\lambda_0}{2\cos(\gamma)}, \tag{1}$$

providing longitudinal-mode selection. The idea in this arrangement is that because of the limited extension of the inner spot, even transverse-mode selection should be possible. Therefore no resonator or external optical element is needed, and hence this Bessel-beam-pumped DFB laser is superradiant and, at the same time, capable of single-mode operation.

3. Experiment

In our experiment we pumped the dye with a *Q*-switched frequency-doubled Nd:YAG laser. The pump pulses had an energy between 40 and 150 mJ and a pulse duration of 10 ns. The laser light shows a coherence length of 1 cm, which is quite enough to achieve high modulation of the interference pattern in the standing wave. As shown in Fig. 1, our setup allows us to vary the Bessel angle γ and thus the wavelength of the standing Bessel wave in the dye.[20] An axicon is inserted into a telescope consisting of two lenses, L_1 and L_2, hence a ring focus is formed in their common focal plane. Thus the angle γ of the resulting Bessel beam depends on the position of the axicon between the lenses, according to

$$\tan\gamma = L\tan(\gamma_0)\left(\frac{1}{f_2} - \frac{1}{L}\right), \tag{2}$$

where γ_0 is the angle of an on-axis beam after it has passed the axicon and is given as $\gamma_0 = (n-1)\delta$, with n as the refractive index of the axicon and δ as its basis angle. L is the distance between the axicon and the second lens, and L is the free parameter to be varied in order to vary γ.[21]

The obtained Bessel beam was reflected by the silvered rear side of a cuvette that contained a solution of fluorescein 27 dissolved in alkalic methanol (KOH in methanol, pH = 8). In order to take degraded dye out of the active region, the dye was continuously pumped through the cuvette. Methanol as a solvent shows a very low optical Kerr effect.[22] In our geometry a pump pulse of 50 mJ would lead to a variation of the refractive index of less than 10^{-3}.

The concentration of the dye has to fulfill the demands that the laser has a low threshold and that the self-lasing wavelength lies near the pump wavelength. The latter is necessary to be able to use Bessel beams that are not too steep [see Eq. (1)]. We determined the optimum length of the cuvette and the concentration of the dye with a superradiant Bessel laser. In a cuvette with a length of 3 mm the optimum concentration was found to be 0.2 g/L (5×10^{-4} mol/L). In this case we achieved a threshold energy near 20 mJ for a Bessel pump beam.

It is clear that the present configuration is not optimized with respect to the laser efficiency, because only a small fraction of the Bessel-beam power is associated with the central intensity filament, and the rest is absorbed elsewhere in the dye. This drawback may be overcome by using a glass plate with a thin borehole that restricts the dye to the high-intensity region instead of a cuvette.[1] We do not, however, dwell on the details of the design here.

The self-lasing wavelength, which is the wavelength of highest gain in the dye pumped with a Gaussian beam, was 545 nm for this concentration.[1,23] With a small mirror, the fluorescence laser beam was reflected into a monochromator with a spectral resolution of 1 nm. A slight misalignment of the mirror causes the laser output signal to vanish, as is expected when the axis of the pump beam is not coincident with the axis of the reflected beam. Laser action was thus observable only if the interference pattern was present.

In order to change the wavelength of the gain variation in the dye, hence to tune the lasing wavelength, the steepness γ of the Bessel beam was varied. The measured and the expected wavelengths are shown in Fig. 2 versus the steepness of the Bessel beam. We were able to tune the obtained laser output wavelength over 4 nm, but it was not possible to reach a wavelength below the self-lasing wavelength of $\lambda_s = 545$ nm.

4. Discussion

In Fig. 2 the measured wavelength of the DFB laser is plotted versus the Bessel cone angle γ_L in air. At small angles γ_L the output had been exactly the self-lasing wavelength λ_s. With increasing γ_L, the output wavelength increases slowly and reaches the solid curve at higher angles. The solid curve shows the Bragg wavelength of the DFB laser according to Eq. (1).

Although this result demonstrates the tunability of the laser output, the measured wavelength is not what one would expect from the Bragg effect. For small angles γ ($\leq 10°$) this behavior can be explained by the gain efficiency of the dye, which is also displayed in Fig. 2. The Bragg wavelength does not lie within the gain region, so there is a situation of lasing at highest gain that is not influenced by the spatial modulation of the pump field.

Quantitative explanation of the values of the output wavelength at higher angles is difficult. Because of the absorption of light in the dye, the nearly longitudinal pumping scheme results in a spatial

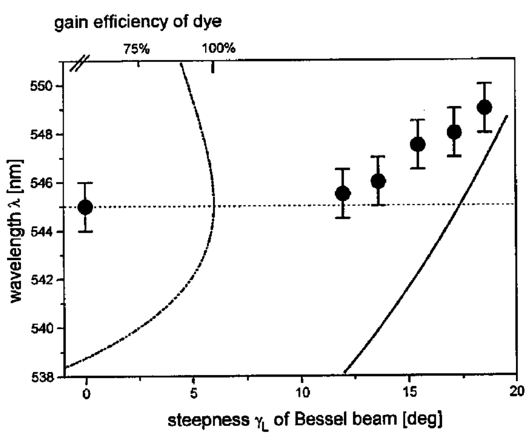

Fig. 2. Results and gain curve: the solid curve represents the Bragg wavelength plotted against the angle γ_L of the Bessel beam in the air. We also plotted the gain efficiency of the dye in the left-hand part of the figure (dotted–dashed curve). The horizontal dashed line gives the wavelength of maximum gain.

dependence of the amplitude of gain modulation. The gain profile is not constant over the tuning range, as assumed in theories of DFB lasers.[7,24] Also, saturation effects in the dye or thermal effects might contribute to shifting of the output frequency. Another possible explanation is that the amount of index variation is not negligible, because it has been shown[24] that, for systems with combined index and gain modulation, the output frequency is decreased relative to the Bragg frequency. Because the intensity pattern in the dye is rather complicated, a detailed explanation would be a formidable numerical task.

In conclusion, we have demonstrated that Bessel beams may be useful for pumping tunable dye lasers, because of their long and thin line focus and the tunability of their effective wavelength. Just by moving an axicon, we changed the DFB wavelength, which allows us to tune the output laser frequency.

References

1. F. P. Schäfer, *Dye Lasers,* F. Schäfer, ed. (Springer-Verlag, Berlin, 1990), Chap. 1, pp. 1–89.
2. H. Kogelnik and C. V. Shank, "Stimulated emission in a periodic structure," Appl. Phys. Lett. **18,** 152–154 (1971).
3. C. V. Shank, J. E. Bjorkholm, and H. Kogelnik, "Tunable distributed-feedback dye laser," Appl. Phys. Lett. **18,** 395–396 (1971).
4. Y. Cui, T. N. Ding, D. L. Hatten, W. T. Hill III, and J. Goldhar, "Frequency tuning of a distributed feedback dye laser with two transmission gratings," Appl. Opt. **32,** 6602–6606 (1993).
5. J. Jasny, "Novel method for wavelength tuning of distributed feedback lasers," Opt. Commun. **53,** 238–242 (1985).
6. Z. Bor, "Amplified spontaneous emission from N_2-laser pumped dye lasers," Opt. Commun. **39,** 383–386 (1981).
7. H. Kogelnik and C. Shank, "Coupled-wave theory of distributed feedback lasers," J. Appl. Phys. **43,** 2327–2335 (1972).
8. F. Kneubühl and M. Sigrist, *Laser* (B. G. Teubner, Stuttgart, Germany, 1989).
9. J. Durnin, "Exact solutions for nondiffracting beams: I. The scalar theory," J. Opt. Soc. Am. A **4,** 651–654 (1987).
10. J. Durnin, J. Miceli, Jr., and J. Eberly, "Diffraction-free beams," Phys. Rev. Lett. **58,** 1499–1501 (1987).
11. J. Turunen, A. Vasara, and A. T. Friberg, "Holographic generation of diffraction-free beams," Appl. Opt. **27,** 3959–3961 (1988).
12. G. Häusler and W. Heckel, "Light sectioning with large depth and high resolution," Appl. Opt. **27,** 5165–5169 (1988).
13. M. Florjanczyk and R. Tremblay, "Guiding of atoms in a traveling-wave laser trap formed by the axicon," Opt. Commun. **73,** 448–450 (1989).
14. T. Wulle and S. Herminghaus, "Nonlinear optics of Bessel beams," Phys. Rev. Lett. **70,** 1401–1404 (1993).
15. J. H. McLeod, "The axicon: a new type of optical element," J. Opt. Soc. Am. **44,** 592–597 (1954).
16. G. Indebetouw, "Nondiffracting optical fields: some remarks on their analysis and synthesis," J. Opt. Soc. Am. A **6,** 150–152 (1989).
17. F. P. Schäfer, "On some properties of axicons," Appl. Phys. B **39,** 1–8 (1986).
18. G. Kuhnle, G. Marowsky, and G. A. Reider, "Laser amplification using axicon reflectors," Appl. Opt. **27,** 2666–2670 (1988).
19. W. M. Wood, G. Focht, and M. C. Downer, "Tight focusing and

blue shifting of millijoule femtosecond pulses from a conical axicon amplifier," Opt. Lett. **13,** 984–986 (1988).
20. K. B. Wolf, "Diffraction-free beams remain diffraction free under all paraxial transformations," Phys. Rev. Lett. **60,** 757–759 (1988).
21. A. T. Friberg, A. Vasara, and J. Turunen, "Partially coherent propagation-invariant beams: passage through paraxial optical systems," Phys. Rev. A **43,** 7079–7082 (1991).
22. N. Harrison and B. Jennings, "Laser-induced Kerr constants for pure liquids," J. Phys. Chem. Ref. Data **21,** 157–163 (1992).
23. F. Bos, "Optimization of spectral coverage in an eight-cell oscillator-amplifier dye laser pumped at 308 nm," Appl. Opt. **20,** 3553–3556 (1981).
24. S. Gnepf and F. K. Kneubühl, "Theory on distributed feedback lasers with weak and strong modulations," in *Infrared and Millimeter Waves,* J. K. Button, ed. (Academic, Orlando, Fla., 1986), Vol. 16, Chap. 2, pp. 35–76.