270

LINE NARROWING AND SPECTRAL HOLE BURNING IN SINGLE MODE Nd^{3+}-FIBER LASERS

M. Zürn, J. Voigt, E. Brinkmeyer, and R. Ulrich

Technische Universität Hamburg-Harburg,

D-2100 Hamburg 90, Federal Republic of Germany

and

S.B. Poole

Department of Electronics, University of Southampton

United Kingdom, SO9 5NH

Abstract

Line-narrowing in the output spectrum of an Nd-doped silica-fiber laser with spectrally flat reflectors is interpreted to indicate substantial homogenous contribution to the 1.09 μm fluorescent linewidth. Using a fiber Bragg-reflector, frequency-stable operation with 100 GHz bandwidth is obtained, dominated by power broadening and spectral hole burning.

Indexing Terms

Fiber-laser; Neodymium lasers; Lasers and applications; Single mode fibers

Laser-action in Nd-doped single mode fibers [1,2] is of interest for applications in fiber optic sensing and signal processing, because such lasers can be pumped conveniently with semiconductor sources and are tunable over a wide spectral range. For many of the possible applications it is desirable that the laser has the narrowest possible linewidth. The line broadening mechanisms relevant for achieving a narrow linewidth in an Nd-fiber laser are discussed in this letter.

Concerning linewidths, there exists a striking similarity of Nd-fiber lasers and index guided semiconductor lasers. Below threshold, both types of lasers have emission spectra of roughly comparable bandwidths near their main laser transitions. Above threshold, again, Nd-doped fiber lasers behave similar to semiconductor lasers as they, too, can concentrate the major part of their fluorescent emission into a narrow laser line. This fact points to *homogeneous* line broadening mechanisms in both types of lasers.

On the other hand, the line broadening mechanisms are known to be physically different in the two types of lasers. In semiconductor lasers, the band-band laser transition is *homogeneously* broadened to a width $\Delta\nu_h \cong 300$ cm^{-1}. Therefore, they can switch spontaneously into single line operation [3,4] with bandwidths down to 10^4 Hz if a moderately frequency selective reflector is used in connection with a long cavity. In Nd-doped silica fibers, the dominant $^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence band at $\lambda \cong 1.09$ μm has a width $\Delta\nu_i \cong 200$ cm^{-1} that is believed to result primarily from *inhomogeneous* broadening due to the statistical distribution of the Nd^{3+} ions in the glass matrix.

Consequently, when operating with a narrow band reflector, only a small fraction of the entire Nd-population should be expected to lase, with a correspondingly small output power, proportional to the homogeneous linewidth within the inhomogeneous line [5]. This expectation is not confirmed, however, by the observation of JAUNCEY et al. [6] and of ourselves [7], i.e. that the laser output power remains essentially unchanged when a narrow-band reflector is substituted for one with a broad reflection characteristic.

As an explanation of this behaviour we propose two mechanisms of homogeneous broadening. One results from the 6-fold 'crystal' field splitting of the lower laser level. Actually, each individual Nd^{3+} ion has 6 discrete $^4I_{11/2}$ sub-levels that are supposed to be spread out over a spectral range of $\Delta\nu_6$, whose width is of the order of 100...500 cm^{-1} in various crystalline host materials [8]. In silica, a similar width may be expected. In the absence of crystal symmetry, lasing transitions are allowed into each sub-level, so that they all may act jointly as one quasi-homogeneous line of width $\Delta\nu_6$. The other homogeneous broadening mechanism is saturation broadening [5] due to the high optical power density that results from the narrow cross section of a single mode optical fiber already at power levels of 0.1 mW. As a consequence of these two broadening mechanisms, the output spectrum of an Nd-fiber laser appears to be governed by a modified form of ***spectral*** hole burning that involves the 6 sublevels of each Nd^{3+} ion. Moreover, it appears likely that ***spatial*** hole burning is the mechanism that prevents spontaneous single line operation of the simple Nd fiber laser.

These interpretations are supported by a group of experiments with an Nd fiber laser that we operated with various kinds of reflectors, see Fig. 1. The fiber is doped with 3000 ppm (by weight) of Nd in its core of diameter $2a \cong 4\ \mu m$. Typically, lengths of $L \cong 1$ m were employed. Their end faces are carefully cleaved (angular error $\leq 0.5°$) and coated with 5-layer (HLHLH) dielectric mirrors of ZnS and MgF_2. The layers are designed to be $\lambda/4$ near the laser transition frequency, $\nu \cong 9200\ cm^{-1}$ (or 1.09 μm wavelength). Here, the mirrors provide a high reflectivity ($R \cong 0.74$) with a fairly flat spectral dependence. Simultaneously they pass with low reflection loss ($R \leq 0.02$) the 541.5 nm pump light from an Ar^+ ion laser, see Fig 1. From a measurement of scattered pump light along the fiber we determined the pump absorption rate to be (7 ± 1) dB/m.

Several fibers were prepared in this way, all showing CW laser action in the simple arrangement of Fig 1(a). The laser output spectrum $S(\nu)$ is monitored in real time by a beam splitter, 0.6 m grating spectrometer, and CCD detector array. The laser threshold is typically near 2 mW of absorbed pump power, as determined from the pump power emerging from the far fiber end and from the absorption rate mentioned above. The slope efficiency is of the order of 6 %. These fiber lasers show pronounced relaxation oscillations whose frequencies vary with the pump rate $r = P_{PUMP}/P_{THRESHOLD}$. The observed frequencies (30 - 80 kHz) are in good agreement with the well-known [5] relationship $4\pi^2 f^2 \tau t_c = (r-1)$. Here, $\tau \cong 470\ \mu s$ is the spontaneous lifetime [2] of the upper laser level and $t_c = n[-(c/2L)\ln R_1R_2]^{-1}$ is the cavity decay time, with $n \cong 1.45$ denoting the effective index and $R_1 = R_2 = 0.74$ the mirror reflectivities.

The output spectrum must consist of a large number of (non-resolved) cavity modes spaced $\Delta\nu = 1/2nL \cong 0.003\ cm^{-1}$ apart. With the mentioned reflector, the spectrum is found to have a fairly smooth envelope with a flat top, see Fig. 2a. Its width $\Delta\nu_L$ is considerably narrower than what should be expected if the fluorescence line were *inhomogeneously* broadened. The measured shape of that line [2] is shown in Fig. 2(d). When the pump rate is increased, laser action starts (r=1) at the top of that spectrum, near $\nu = 9200\ cm^{-1}$. At slightly higher pump rates r>1, simple laser theory would require for a strongly inhomogeneously broadened line that the laser spectrum broadens to the width $\Delta\nu_F(r)$ of the fluorescence spectrum measured at a relative height 1/r from the peak. Only within this width, modes are above threshold. The actually observed widths (Fig. 3) are narrower by a factor of ≃ 5. This spontaneous line narrowing with a spectrally flat reflector, existing all the way down to the threshold (r → 1), shows the existence of strong *homogeneous* line broadening to the shape of the 1.09 μm fluorescence band of the Nd^{3+} silica fiber.

In addition , there exists of course strong *inhomogeneous* broadening. This be- comes evident in the resonator configuration with a Fabry-Pérot (F.P.) reflector, see Fig. 1(b). That reflector is formed by the combination of the multilayer coating on the second fiber end face with an external aluminium front surface mirror M, separated by a coupling gap s from the fiber end. The resulting reflection spectrum $R_2(\nu)$ is periodic with a spacing $\Delta\nu_s = 1/2s$ between adjacent orders. In the limit of $s \rightarrow 0$, these orders may be characterized by a calculated finesse $F \leq 15$, but practically F is much lower. When the gap is small ($s \leq 25$ μm), so that the spacing of orders is large ($\Delta\nu_s \geq 200$ cm^{-1}) compared to the fluorescence bandwidth, the envelope of the resulting laser spectrum consists typically of a single F.P. order, as indicated by the solitary peak (dashed line) in Fig. 2(b). By piezoelectric variation of s, the spectral position of this peak can be tuned continuously within a range $\Delta\nu_T$ that is approximately 1.5 times broader than the spectrum $\Delta\nu_L$ of the laser with a flat reflector, see Fig. 3. The spectral width of that peak is typically $\Delta\nu_{FP} \cong 15$ cm^{-1}, corresponding to 450 GHz, which is considerably narrower than the width $\Delta\nu_s/F$ of the F.P. reflection spectrum. In the limit of large reflector spacings, $s \rightarrow \infty$, the fraction R_M of power reflected by M back into the fiber core becomes very small due to the angular spreading of the fiber output beam. By simple geometrical optics we estimate $R_M \cong (a/2s\theta)^2$. Here, $\theta \cong 0.2$ rad denotes the angular aperture of the fiber. Because $R_M \ll 1$, the reflectivity $R_2(\nu)$ varies sinusoidally about its average $\bar{R}_2 = 0.74$ with a small amplitude $2\ (\bar{R}_2 R_M)^{0.5}$ that vanishes continously as $s \rightarrow \infty$. As the order spacing $\Delta\nu_s = 1/2s$ gets smaller, the laser spectrum contains an increasing number of discrete lines, each representing an F.P. order, see Fig. 2(b). For $s \geq 300$ μm, these lines extend over essentially the same spectral range $\Delta\nu_L$ as the laser spectrum with a spectrally flat reflector. This line structure of the envelope spectrum is observed out to a spacing of s = 30 mm, corresponding to a feedback of the order of −75 dB of optical power. The described large lasing bandwidths and the wide tunability and variability of the envelope spectrum indicate clearly the existence of the *inhomogeneous* component of line broadening of the fluorescent band.

The existence of a very substantial homogeneous broadening within this inhomogeneously broadened line, discussed already above, is further demonstrated by the observations of spectral hole-burning and of the relationsship between laser linewidth $\Delta\nu_L$ and laser power. In an effort to narrow down the laser linewidth, the pigtail of a fiber Bragg reflector [4,7] was butt-coupled by a micro-positioner to the multilayer-coated laser fiber, see Fig. 1(c). The Bragg reflector is formed by a photoresist relief grating on the flat surface of a side-polished fiber that is identical to the laser fiber but undoped. The grating constant g = 375 nm is chosen so that the peak frequency of Bragg reflection, $\nu_B = 1/2ng \cong 9130\ cm^{-1}$, falls right into the laser band. From the radius of curvature (300 mm) of the side polished fiber we calculate [4] a full (e^{-2} power-) width of $\Delta\nu_B \cong 3\ cm^{-1}$ (or 90 GHz) of the Bragg reflection spectrum $R_B(\nu)$. The associated peak reflectivity is not known exactly but is estimated to be of the order $R_{MAX} \cong 0.2$. It depends strongly on the state of polarization. The length of the fiber pigtail from the Bragg reflector to the butt coupling point is ≈ 300 mm.

With the Bragg reflector coupled strongly to the laser fiber ($s \leq 25\ \mu m$), the laser operates stably on the Bragg frequency ν_B, regardless of the pumping level and of the fine adjustment of the coupling gap s. This observation is in accordance with [6], where such a fiber Bragg reflector had been spliced directly to the lasing fiber. The output power and slope efficiency are higher by a factor of ≈ 1.25, and the threshold is lower by a factor of ≈ 1.2 than in the laser configuration Fig. 1(a), i.e. for $s \to \infty$. An analysis of the relaxation frequency shows that these changes may be explained by an increase of the overall reflectivity R_2 from 0.74 to 0.78.

The linewidth of the fiber laser operating this way with the Bragg reflector is ≅ 100 GHz. This value slightly exceeds the calculated width of the reflector, and is moreover of the same order of magnitude as the minimum width obtained with the F.P. reflector. We conclude that the fiber laser, unlike a semiconductor laser in a comparable situation [4], does *not* switch spontaneously into single longitudinal mode operation. Rather, if such an operation existed, it would be unstable due to the presumably very low mobility of the optical excitation energy in the weakly doped silica. Consequently *spatial* hole burning would result, accompanied by a built-up of gain for the oscillation of neighbouring longitudinal modes.

When the width of the coupling gap is increased to s = 50 - 100 μm, the dominance of the Bragg peak in the reflection spectrum $R_2(\nu)$ is reduced. The peak becomes comparable to the Fabry Perot type structure of $R_2(\nu)$ that results from Fresnel reflections at the two fiber end faces forming the coupling gap. As a consequence, the fiber laser operates simultaneously at the fixed Bragg frequency ν_B and at a number of equidistantly spaced F.P. lines whose positions tune with s. When the Bragg line is not operating (e.g. after a small lateral offset of the Bragg fiber at the butt coupling point) these F.P. lines tune continuously over the width ν_T with a broad, smooth envelope. With the Bragg-line operating, however, a well pronounced "hole" is observed that extends over a distance of 10 - 50 cm^{-1} to either side of the Bragg line. When the gap width is tuned and an F.P. line approaches the Bragg line, that F.P. line decreases in intensity and vanishes, while the Bragg line itself is not affected. Upon further tuning, the F.P. line re-emerges on the other side of the hole. For a typical situation (s = 25 μm), this hole is illustrated in Fig. 2(c) by the tuning envelope of the F.P. lines. The hole broadens when the power P_B in the Bragg line is increased, e.g. by varying the coupling conditions. A rough estimate yields a width of $\Delta\nu_{hole} \cong 20$ cm^{-1} (measured at half the depth of the hole) in this situation of finite power in the F.P. lines. Standard laser theory [5] gives the power where saturation effects start to be dominant: $P_{sat} = 4\pi^2 n^2 h\nu\Delta\nu_h A/\lambda^2 \cong 70$ μW (n is the refractive index of the fiber, h is Planck's constant, and A the fiber cross section). The homogeneous linewidth $\Delta\nu_h$ to be used here is not the spread $\Delta\nu_6$ of the 6 sublevels, however, but the width ($\cong$ 15 cm^{-1}) of transitions to individual sublevels. As most experiments with this fiber reported here and elsewhere were performed at internal powers far exceeding P_s, saturation effects clearly play a dominant role.

In conclusion, we have shown that the output spectrum in the principal 1.09 μm band of an Nd^{3+}-doped silica fiber laser can be understood to result from a combination of homogeneous and inhomogeneous line broadening. Both effects combine in the spectral hole burning phenomenon when the laser power exceeds $P_S \cong 70\ \mu W$.

We gratefully acknowledge the fruitful cooperation with D.N. Payne of the University of Southampton and stimulating discussions with H.G. Danielmeyer of the Technische Universität Hamburg-Harburg.

Figure Captions

Fig. 1 Cavity configurations of Nd^{3+} fiber laser,

(a) with two spectrally flat multilayer mirrors,

(b) with a Fabry-Pérot reflector at one end, formed by the addition of mirror M,

(c) with fiber Bragg reflector at one end.

Fig. 2 Output spectra of Nd^{3+} fiber laser, Curves (a), (b), and (c) correspond to the laser configurations of Figs. 1(a), (b), (c), respectively; curve (d) is the spontaneous emission spectrum according to Ref. [2].

Fig. 3 Spontaneous emission bandwidth $\Delta\nu_F(r)$ according to Ref. [2], tuning width $\Delta\nu_T(r)$, and laser width $\Delta\nu_L(r)$ versus normalized pump rate r.

References

[1] MEARS, R.J., REEKIE, L., POOLE, S.B., and PAYNE, D.N., 'Neodymium-doped silica single-mode fibre lasers', Electron. Lett., **21**, 738-740 (1985)

[2] REEKIE, L., MEARS, R.J., POOLE, S.B., and PAYNE, D.N., 'Tunable Single Mode Fiber Lasers', J. o. Lightwave Tech., **LT-4**, 7, 956-960 (1986)

[3] WYATT, R. and DEVLIN, W.J., '10 kHz Linewidth 1.5 μm InGaAsP External Cavity Laser with 55 nm Tuning Range', Electron. Lett., **19**, 110-112 (1984)

[4] BRINKMEYER, E., BRENNECKE, W., ZüRN, M., and ULRICH, R., 'Fibre Bragg Reflector for Mode Selection and Line-narrowing of Injection Lasers', Electron. Lett., **22**, 134-135 (1986)

[5] YARIV, A., 'Optical Electronics', Holt, Rinehart, and Winston, New York, NY (1976)

[6] JAUNCEY, I.M., REEKIE, L., MEARS, R.J., PAYNE, D.N., ROWE, C.J., REID, D.C.J., BENNION, I., EDGE, C., 'Narrow-Linewidth Fibre Laser with Integral Fibre Grating', Electron. Lett., **22**, 987-988 (1986)

[7] ZüRN, M., and ULRICH, R., 'Integriert/Faseroptischer Braggreflektor zur Frequenzstabilisierung von Lasern', Kolloquium 'Integrierte Optik' der Deutschen Forschungsgemeinschaft, Paderborn, Apr. 24, 1986.

[8] KAMINSKII, A.A., 'Laser Crystals', Springer-Verlag, Berlin, 122 (1981)

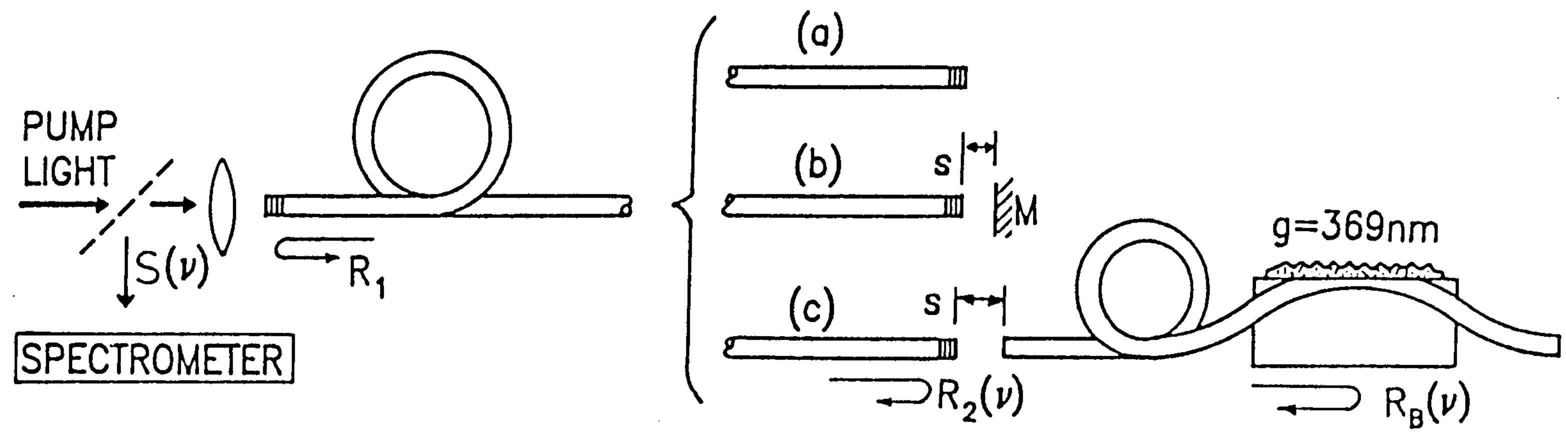


Fig. 1

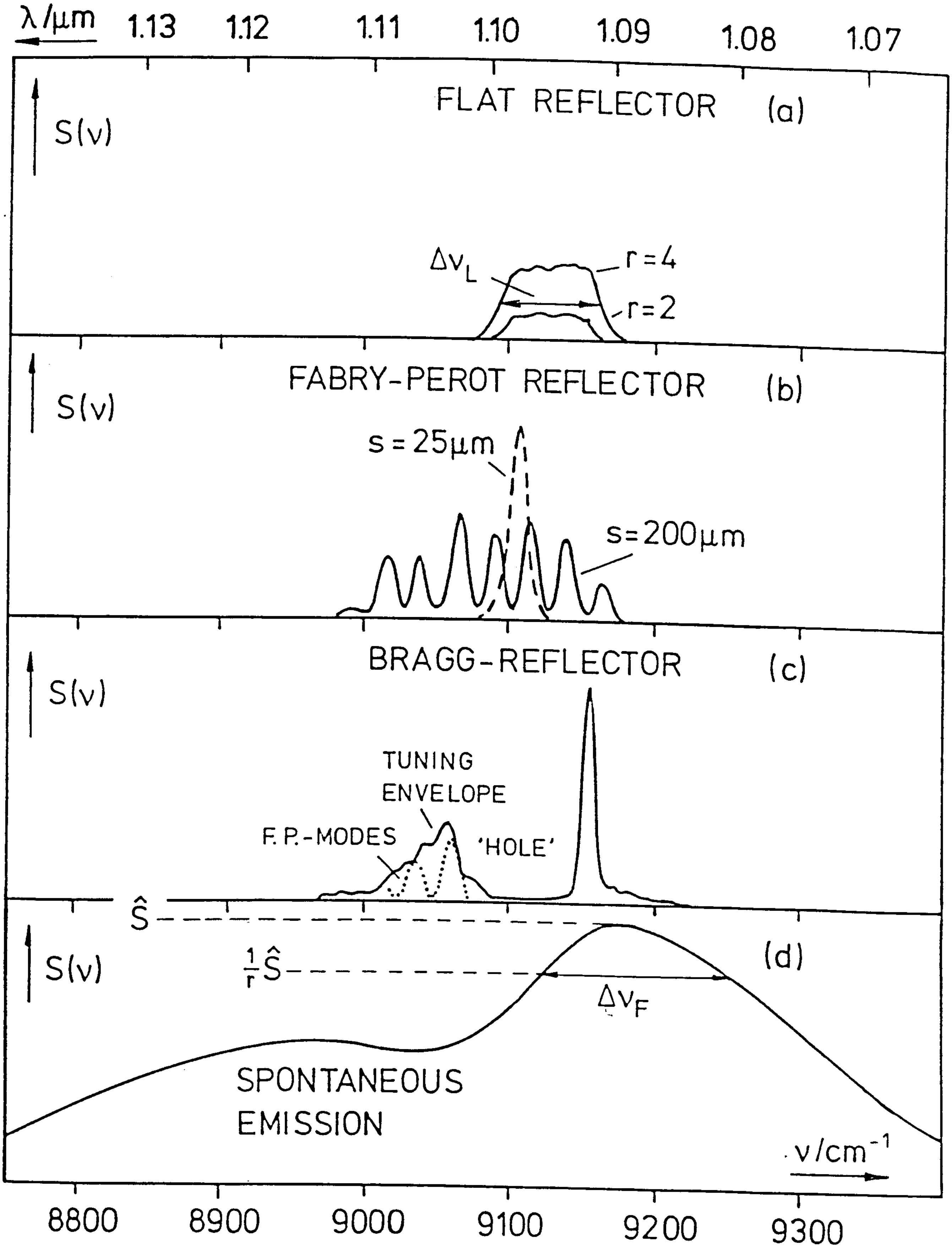
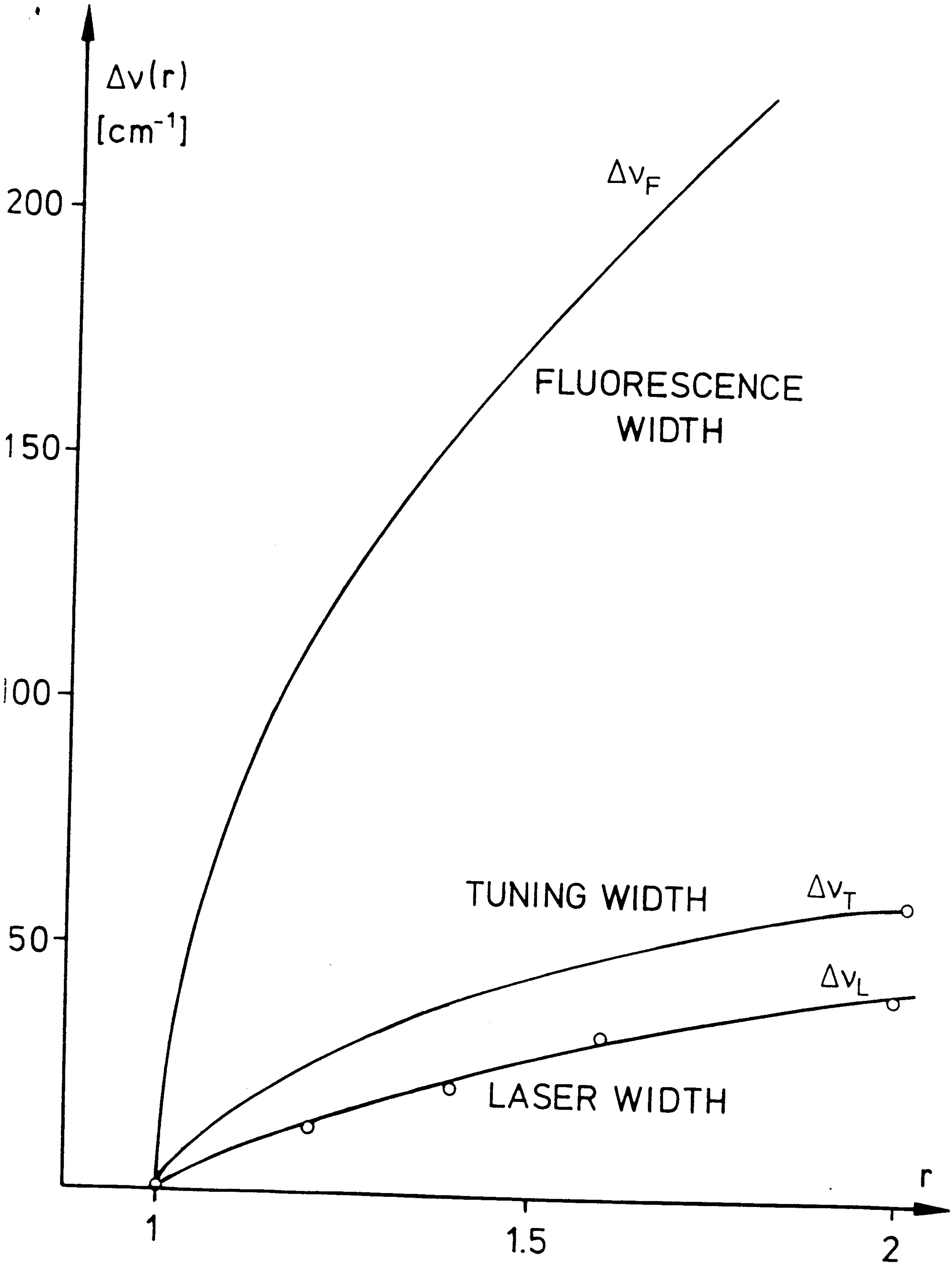

λ/μm
1.13
1.12
1.11
1.10
1.09
1.08
1.07
FLAT REFLECTOR
(a)
S(ν)
Δν_L
r=4
r=2
FABRY-PEROT REFLECTOR
(b)
S(ν)
s=25μm
s=200μm
BRAGG-REFLECTOR
(c)
S(ν)
TUNING
ENVELOPE
F. P.-MODES
'HOLE'
Ŝ
(d)
S(ν)
1/r Ŝ
Δν_F
SPONTANEOUS
EMISSION
ν/cm⁻¹
8800
8900
9000
9100
9200
9300

Fig. 2



Δν(r)
[cm⁻¹]
200
150
100
50
Δν_F
FLUORESCENCE WIDTH
TUNING WIDTH
Δν_T
Δν_L
LASER WIDTH
r
1
1.5
2

Fig. 3