Intracavity gain gratings

Aurélie Moreau, Quiong He, Isabelle Zaquine, Alain Maruani, Robert Frey

Intracavity gain gratings

Aurélie Moreau, Qiong He, Isabelle Zaquine, and Alain Maruani

GET/Télécom Paris, CNRS/LTCI, 46, rue Barrault, 75634 Paris Cedex 13, France

Robert Frey

GET/Télécom Paris, CNRS/LTCI, 46, rue Barrault, 75634 Paris Cedex 13, France, and Laboratoire Charles Fabry de l'Institut d'Optique, CNRS et Université Paris Sud, Centre Scientifique Paris Sud, Bâtiment 503, 91403 Orsay Cedex, France

Intracavity gain gratings are theoretically demonstrated to exhibit diffraction efficiencies that are 100 times larger than unity at pump powers substantially below the lasing threshold. Experiments performed using a Nd:YVO$_4$ microlaser pumped below threshold by two interfering Ti:sapphire laser beams are described. Huge enhancement of the diffraction efficiency (5000×) and a large increase of the angular selectivity (10×) are demonstrated despite the angular reduction of the Fabry–Perot cavity finesse. Much better results are expected using gain gratings with larger areas or thinner cavities such as vertical cavity surface-emitting lasers. Such large fan-out values could be very interesting for applications to optical signal processing. © 2007 Optical Society of America

OCIS codes: 050.1950, 050.2230, 140.4480.

Diffraction of light on Bragg gratings has attracted much attention for fundamental reasons and for applications to optical signal processing.[1,2] However, the low refractive index modulations or the small thicknesses of the nonlinear materials used for recording the gratings make such devices insufficient for practical applications. These limitations can be overcome by inserting the grating in a Fabry–Perot cavity. The resulting substantial improvement of the diffraction efficiency, angular selectivity, and cross talk has been demonstrated through calculations[3] and experiments.[4] Moreover, such a device was shown to exhibit a Bragg diffraction regime in a very thin nonlinear medium.[5] Diffraction efficiencies larger than unity were predicted for refractive index gratings placed inside amplifying Fabry–Perot cavities.[6] Such devices are very interesting since they provide the large fan-out values often required for applications to optical signal processing. In this Letter, we demonstrate both analytically and experimentally that intracavity gain gratings can give even better results with devices as simple as Nd:YVO$_4$ microlasers.

The intracavity Bragg device considered in our study is composed of a sinusoidal gain grating of period Λ and amplitude modulation Δg recorded in an amplifying material of mean gain g. This material entirely fills a Fabry–Perot cavity of thickness L. The front mirror, M$_1$, has an energy reflection coefficient R_1. The back mirror, M$_2$, is nearly totally reflecting ($R_2 \approx 1$) to get a single diffracted beam of intensity I_{RD} counterpropagating the incident read beam of intensity I_I and wavelength λ. The geometry of the analyzed device is shown in Fig. 1 of Ref. 3. The amplifying cavity is supposed to be pumped below lasing threshold. The diffraction efficiency $\rho = I_{RD}/I_I$ and amplification $A = I_T(g)/I_T(0)$ [with $I_T(g)$ the small intensity transmitted by the amplifying Fabry–Perot cavity with no grating] of the device are calculated following the method developed in Ref. 3. However, as in Ref. 6 a complex wave vector, $k = k' + ik''$, in the direction of the phase velocity is used to take the amplification into account. The real and imaginary parts of k are $k' = 2\pi_{n_0}/\lambda$ and $k'' = g/2$, respectively, where n_0 and g are the mean refractive index and the gain coefficient of the intracavity amplifying medium, respectively. In this study we shall deal with a gain grating rather than a refractive index modulation. It is then straightforward to obtain, when both Bragg ($\lambda = 2n_0\Lambda \sin \theta$) and Fabry–Perot ($2n_0 L \cos \theta = p\lambda$, with p integer) resonance conditions are fulfilled,

$$\rho = \frac{(1 - R_1)^2 R_2' \sinh^2(2\xi)}{[1 + R_1 R_2' - 2\sqrt{R_1 R_2'} \cosh(2\xi)]^2}, \quad (1)$$

$$A = \frac{\exp(xg_0 L)[1 + R_1 R_2 - 2\sqrt{R_1 R_2}]}{1 + R_1 R_2' - 2\sqrt{R_1 R_2'}}, \quad (2)$$

with $R_2' = R_2 \exp(2gL/\cos \theta)$ and $\xi = \Delta g L/(4 \cos \theta)$, where θ is the angle of refraction of the read beam in the intracavity medium.

Figure 1 shows the diffraction efficiency and the read beam amplification plotted as a function of the normalized pump power $x = P/P_{th}$, where P_{th} is the lasing threshold power. This threshold is characterized by the equality $1 + R_1 R_2'(g_{th}) - 2\sqrt{R_1 R_2'(g_{th})} = 0$ (with g_{th} proportional to the pump power P_{th} in the amplifying medium model considered in our analysis). Results of Fig. 1 were calculated for a Nd:YVO$_4$ microlaser with $R_1 = 0.95$, $R_2 = 1$, $L = 1$ mm, $g = xg_{th}$, and $\Delta g = 0.6xg_{th}$. As expected, the read beam amplification diverges as P/P_{th} approaches unity. The diffraction efficiency also diverges but at a lower pump value, as can be inferred from Eq. (1). Figure 1 shows
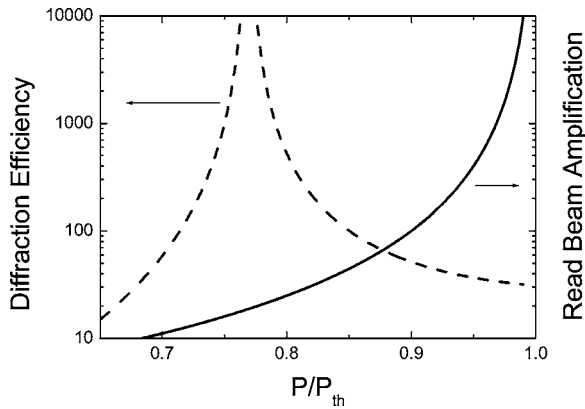
Fig. 1. Calculated diffraction efficiency of the intracavity gain grating and amplification of the read beam plotted as a function of the ratio between the real and threshold pumping powers.
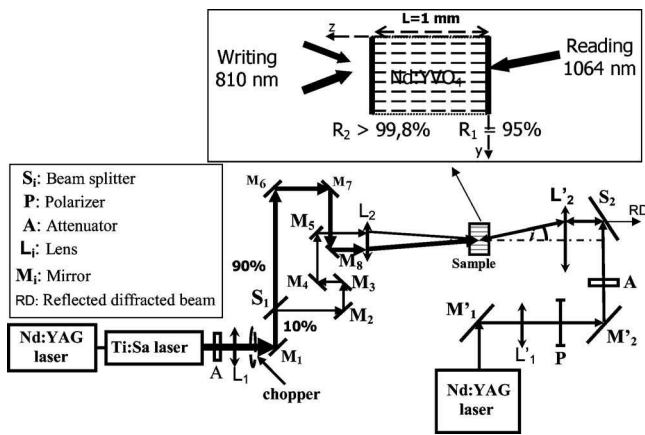

Fig. 2. Experimental setup for writing and reading the gain grating, with an inset showing the sample in more detail.

that diffraction efficiencies larger than 100 may be expected over a large range of pump powers below the threshold power (0.72–0.85 P_{th}). This result is very encouraging for the development of practical devices with high fan-out values.

The principle of the proposed technique was tested using a conventional Nd:YVO$_4$ microlaser. The experimental setup is shown in Fig. 2. The 1 mm long intracavity gain medium is pumped below laser threshold by two interfering beams delivered by the same CW Ti:sapphire laser operating at 810 nm. Due to this modulated pumping achieved through 300 μm diameter beams, a small area intracavity gain grating is written in the microlaser. This grating ($\Lambda \approx 40$ μm) is read at the Bragg angle (exterior incidence angle $i_t \approx 10$ mrad) by a 200 μm diameter Nd:YAG laser beam whose frequency is resonant with the laser cavity. For this asymmetric cavity of finesse $F = \pi \sqrt[4]{R_1 R_2}/(1 - \sqrt{R_1 R_2}) \cong 100$ (the front and back mirrors have reflection coefficients of 95% and 99%, respectively), there is only one significant diffracted beam counterpropagating the read beam and extracted by a beam splitter. Finally, the pump beams are chopped at 25 Hz with a useful opening of 1/400 to avoid undesirable thermal effects.

Measurement of the diffraction efficiency of the device and transmitted read beam amplification were performed using this setup. Results are shown in Figs. 3(a) and 3(b), respectively. Neither amplification nor diffraction efficiency exhibits the asymptotic growth shown in Fig. 1. Actually, the number of overlapping reflected beams in the intracavity grating is limited due to the combination of the small area of the grating and the oblique incidence of the read beam. The Fabry–Perot effective finesse, related to the number of reflected beams effectively interfering in the cavity, is therefore reduced as if the loss of the cavity were increased. This limitation was globally taken into account in the calculations by replacing R_1 with a smaller value $R_1' = 0.90$ in the resonant denominators of Eqs. (1) and (2). The corresponding curves shown in solid curves in Figs. 3(a) and 3(b) confirm the interpretation of the reduction by about a factor of 2 of the finesse of the Fabry–Perot cavity. Evidently this reduction has enormous consequences for the diffraction efficiency and must be avoided if a high fan-out value is required. This drawback, which is linked to the large thickness of the Fabry–Perot cavity, can be avoided by using a larger area gain grating or a thinner cavity, such as a vertical cavity surface-emitting laser, which is only few micrometers thick. Let us note, however, that even in our imperfect experiment the diffraction efficiency reaches more than 20%. This is 5000 larger than the efficiency that would be obtained with the same gain modulation and no cavity. Moreover, diffraction effi-
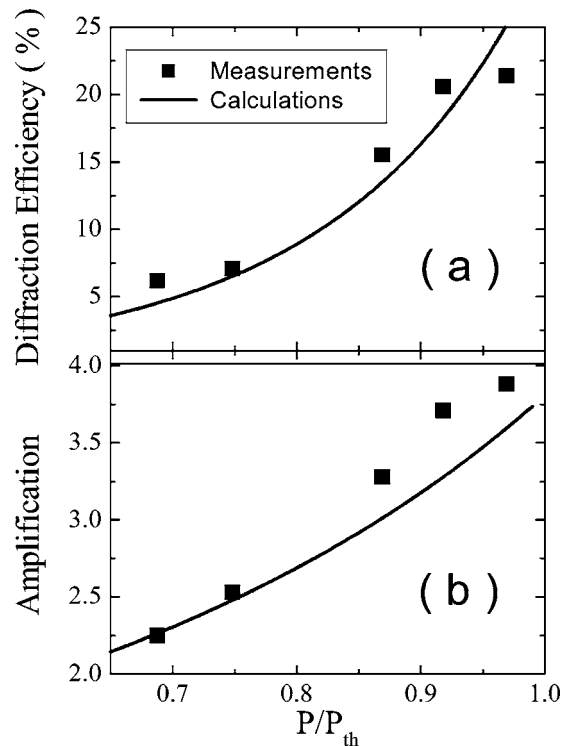

Fig. 3. Measured diffraction efficiency of the intracavity gain grating (a) and amplification of the read beam (b) plotted as a function of the ratio between the real and threshold pump powers (squares). The solid curves correspond to calculations performed using Eqs. (1) and (2) and a reduced value of R_1 (see text).
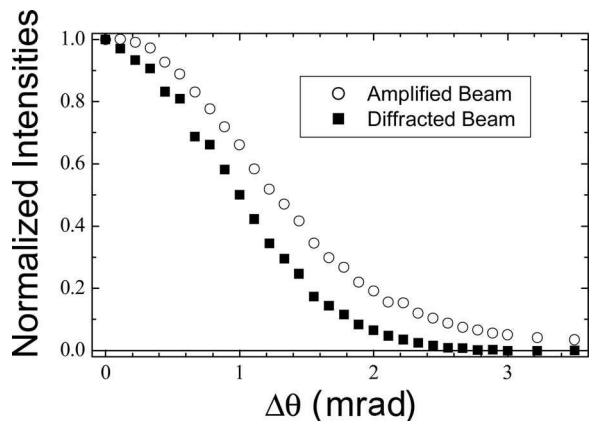
Fig. 4.   Normalized intensities of the diffracted and transmitted beams plotted as a function of the detuning angle.

ciencies larger than unity (nearly 2) were achieved with our setup using a higher modulation depth (50%–50% pump power distribution instead of 90%–10%).

The resolution of the device was also tested by measuring its diffraction efficiency as a function of the detuning angle $\Delta\theta = \theta - \theta_0$ and comparing it with the Fabry–Perot selectivity defined from the cavity transmission. This is illustrated in Fig. 4, showing the normalized diffraction efficiency and the transmission of the device as a function of $\Delta\theta$ (the Bragg and Fabry–Perot resonance angle $i_0 = 13.3$ mrad). The normalized transmitted and reflected–diffracted intensities exhibit almost the same behavior, with a bandwidth (FWHM) of 2.7 and 2.1 mrad, respectively. Note that the resolution of this device is ten times better than that of the same 1 mm long gain grating with no cavity and be could even improved by using a larger area for the gain grating. This high an-

gular selectivity is evidently very important for potential applications to optical signal processing.

Intracavity gain gratings have demonstrated their potential for providing very high diffraction efficiencies (larger than 100 for pump powers substantially below the lasing threshold). This enables the generation of large fan-out values for practical optical signal processors. A huge enhancement of the diffraction efficiency (a factor of 5000 compared with the same gain grating with no cavity) and a strong increase of the angular selectivity (about a factor of 10) were measured for an unoptimized device exhibiting a finesse reduced compared with the ideal Fabry–Perot cavity. Much better results are expected with gain gratings of larger areas or with thinner Fabry–Perot cavities, as in the case of the vertical cavity surface-emitting lasers. All these advantages make intracavity gain gratings very attractive for optical signal processors when large fan-out values are needed.

I. Zaquine's e-mail address is zaquine@enst.fr.

References

1. R. J. Collier, C. B. Burckhardt, and L. H. Lin, *Optical Holography* (Academic, 1971).
2. Y. Ding, D. D. Nolte, M. R. Melloch, and A. M. Weiner, IEEE J. Sel. Top. Quantum Electron. **4**, 332 (1988).
3. L. Menez, I. Zaquine, A. Maruani, and R. Frey, J. Opt. Soc. Am. B **16**, 1849 (1999).
4. L. Menez, I. Zaquine, A. Maruani, and R. Frey, Opt. Lett. **27**, 479 (2002).
5. L. Menez, I. Zaquine, A. Maruani, and R. Frey, J. Opt. Soc. Am. B **19**, 965 (2002).
6. L. Menez, I. Zaquine, A. Maruani, and R. Frey, Opt. Commun. **204**, 267 (2002).