tion the semiconductor diodes used as millimeter-wave mixers and detectors are difficult and expensive to fabricate because of their small size and their high susceptibility to burnout. In comparison, the paramagnetic material used in the downconverter does not have to be small compared to the wavelength and it is virtually indestructible.

A disadvantage of the downconverter is the requirement for expensive and complex refrigeration equipment. The best noise equivalent power is obtained at liquid helium temperature; however, the response time is relatively slow ($\approx 10 \text{ ms}$) at $4^\circ \text{K}$. The response time is improved by three orders of magnitude at liquid nitrogen temperature but the conversion loss is increased by the faster relaxation rates at the higher temperature.

References


Abstract—In this paper we discuss the possibilities and realization in high-power systems of a narrow-band reflector with adjustable high reflectivity and with continuous tuning over a large frequency region. We describe a design for both low- and high-gain systems. For the experimental realization of a low-gain system we used a CO$_2$ laser and studied a continuous range of 65 transitions of the 001-023'0 and 13 transitions of the 011-1110 vibrational band. With a cavity containing a dc discharge 130 cm long, for each band we found a continuous range of single oscillating transitions with output powers up to 15 W. Finally, we propose an experimental solution for continuous tuning of a high-gain system as, for instance, the central part of the 001-1110 vibrational band of CO$_2$.

Introduction

In the search for new oscillating transitions it is desirable to have a narrow-band reflector with high reflectivity, which can be continuously scanned over a large frequency region. A possible solution to this problem is the use of a grating in the Littrow arrangement as one end mirror [1], [2]. This may be particularly attractive for low-power far-infrared or submillimeter systems, where it has been shown that the first-order reflection at the blazed wavelength with polarization perpendicular to the groove length can be above 99 percent [3] or for a low-power high-gain system where high reflectivity is not required [2]. However, such a scheme does not work for low-gain systems in the near-infrared or optical region, where it is found in practice that even at the blazed wavelength the reflectivity is considerably reduced. Furthermore, this scheme is also inadequate for high-power systems as, for instance, a CO$_2$ laser. A possible way to compensate for insufficient first-order reflection of the grating is the use of an additional reflector behind the grating [4] so that the zeroth order, too, is reflected back into the cavity. The effective reflectivity obtained in this way is then limited by the absorption and scattering losses of the grating.

These losses, as we have observed, can be very serious
and depend strongly on the power of the incident radiation [5]. We found 10 percent absorption and scattering losses for an SF-300 grating with gold coating of Oriel Optics when irradiated with 15 W at a wavelength of about 9.2 μ. The high losses and poor power-handling capabilities of a grating seem to detraet seriously from its desirable diffraction properties.

In this paper we shall discuss the possibilities and realization of an outcoupling device that simultaneously offers high-effective reflectivity even for high-power systems together with narrow bandwidth and easy tunability. It consists, in principle, of an optical cavity with one broad-band reflector and a rotatable-wavelength selective grating reflecting in zeroth and first order. It will be shown that this construction will not only lead to considerably higher reflectivity than the Littrow arrangement but, more important, it avoids the exposure of the grating to high power.

The experiments were done with a CO2 laser system having many closely spaced transitions. These transitions are highly competitive in the sense that each of them competes to oscillate not only on its own inversion but on the total inversion of the vibrational levels and their rotational sublevels. As a result, only one or two transitions with the largest gain-to-loss ratio will oscillate [6]. Using a wavelength-discriminating device with sufficient reflectivity, it should be possible to obtain laser action on any low-gain transition irrespective of output power. Therefore we have been especially interested in the low gain transitions with high \( j \) values of the \( P \) and \( R \) branches.

**EXPERIMENTAL CONDITIONS**

Since the output power and mode pattern are influenced by any slight disturbance, the experimental setup, as indicated in Fig. 1, is mounted on a 10-cm-thick 2-by 1-m cast-iron table. Further, the sealed-off laser cavity is formed by the quartz tube with internal mirrors mounted directly at each end. The cavity has a length of 150 cm and an internal diameter of 10 mm. There is a totally reflecting gold-coated mirror with a radius of curvature of 2500 mm on one side and a 36 percent reflecting germanium flat AR coated on the other side. The length of the discharge region is 130 cm. The cavity is strongly over-coupled and would not lase with the usual dc discharge current of 30 mA. The device is water cooled.

The gold-coated diffraction grating has 1800 lines/in and is blazed for 10.6 μ. Together with the 36 percent reflecting germanium flat it forms an additional outcoupling cavity with a length of about 10 cm. The grating is mounted on a tunable piezoelectric translator for position scanning. The grooves of the grating are perpendicular to the optical axis of the system. The translator, with grating, is mounted on an angular orientation device with angular resolution of about 0.1 arc-s. In the region of interest, roughly between 9.1 and 9.7 μ, the zeroth- and first-order reflectivities of the grating are, respectively, 26 and 64 percent for incident intensities of about 15 W. For low-power densities the first-order reflectivity may be considerably higher. In order to suppress higher order modes a 6-mm diaphragm is placed between the grating and the germanium flat. This outcoupling cavity is effectively a Fabry-Perot (FP), where one reflecting surface is the 36 percent reflecting germanium flat and the other one the wavelength-selecting diffraction grating. The first-order reflection on the grating is used for intracavity reflection, whereas the zeroth order reflection is used for outcoupling. Only radiation for which the first-order reflection is parallel to the incident beam can build up a standing wave. This type of FP offers a continuously adjustable narrow-band reflection. In this way any of the available transitions may oscillate if the inversion is sufficient to overcome the comparatively small losses of this outcoupling device. Without the grating the reflectivity of this germanium flat would be too low to obtain oscillations on any transition.

**ANALYSIS**

For a plane wave propagating along the axis of the cavity, assuming the first-order reflection is parallel to the incident beam, one obtains the following expression for the complex amplitude reflectivity

\[
\sqrt{R_{\text{eff}}} e^{i\phi} = -\sqrt{R_1} + \frac{(1 - R_1) \sqrt{R_{21}}}{e^{2i\gamma} - \sqrt{R_1 R_{21}}},
\]

![Fig. 1. Experimental arrangement of laser with transition-selective outcoupling device. The first-order reflection on the grating gives a standing wave, whereas the outcoupled radiation originates from the zeroth-order reflection of the grating.](image)
Here $R_1$ is the intensity reflectivity of the germanium flat and $R_{21}$ is the first-order intensity reflectivity of the grating; $\gamma = \omega L_2/c$ is the optical phase of the outcoupling cavity; $\omega$, $L_2$, and $c$ are the angular radiation frequency, the distance between $M_1$ and $M_2$, and the velocity of light, respectively. The intensity reflectivity $R_{\text{tot}}$ varies between 15 and 89 percent depending on $L_2$ for our experimental parameters. According to (1), the phase shift $\Delta \phi$ for the amplitude reflection depends on the distance $L_2$. This in turn produces a frequency shift of the standing wave in the cavity. The frequency shift is

$$\Delta \nu = -\frac{c}{2L_1} \frac{\Delta \phi}{2\pi} \tag{2}$$

where $L_1 = 150$ cm is the length of the cavity containing the discharge. This frequency shift in turn influences the reflectivity according to (1). However, since $L_1$ is much larger than $L_2$, the latter shift can be neglected. Hence, the reflectivity and frequency change depends only on $L_2$ as described by (1) and (2). The frequency shift is about 25 MHz as the outcoupling cavity is scanned over the high-reflection region. This is well within the Doppler width of any relevant transition. Comparing these values with experimental observations, it turns out that for many transitions the frequency shifts are not more than about 10 MHz.

In the following we assume that absorption and scattering losses on the grating are considerably higher than those on the gold-coated end mirror and transmitting mirror $M_1$. Therefore we consider only the losses on the grating. For our laser cavity with one perfectly reflecting end mirror and a CO$_2$ active medium with homogeneous line broadening [7], the incident radiation $I_0$ on the outcoupling mirror $M_1$ is given by [8]

$$I_1 = \frac{g_0 L_{21} + \frac{1}{2} \ln R_{\text{tot}}}{1 - R_{\text{tot}}} \tag{3}$$

where $I_1$ and $g_0$ are, respectively, the intensity saturation parameter and the small signal gain. From (3) the maximum radiation output is obtained for the maximum value of $R_{\text{tot}}$. The output power $I_{\text{out}}$, leaving the grating, is then

$$I_{\text{out}} = \frac{(1 - R_{21} - \alpha)}{(1 - R_2)} \left( g_0 L_{11} + \ln \left( \frac{\sqrt{R_1} + \sqrt{R_{21}}}{\sqrt{R_1} - \sqrt{R_{21}}} \right) \right), \tag{4}$$

where we used the relation $1 = R_{21} + R_{20} + \alpha$. The parameter $\alpha$ represents the fractional losses on the grating and $R_{20}$ is the zero-order reflectivity of the grating.

In Fig. 2 the calculated radiation intensity according to (4) is plotted versus the first-order reflectivity $R_{21}$ of the grating for several values of the parameter's $g_0 L_{11}$ and $\alpha$. The value of $R_1$ is kept constant and equal to 0.36. From Fig. 2 the maximum value of $I_{\text{out}}$ is obtained if the value of $R_{21}$ decreases with increasing values of $g_0 L_{21}$. This indeed has been observed with our experimental arrangement for strong lines by rotating the grating 180° about its normal. Then, for the same wavelength, $R_{21}$ becomes less and the output was found to increase considerably.

In Fig. 3 we have plotted the maximum output as a function of $R_1$ according to (4) for $g_0 L_{21} = 0.2$ and several values of the parameter $\alpha$. For each value of $R_1$ the calculated radiation is maximized with respect to $R_{21}$ and the corresponding values of $R_{21}$ are also indicated. One may be tempted to consider the seemingly equivalent system, where the positions of the mirror $M_1$ and the grating are interchanged [4] so that the radiation leaving the active medium first passes the grating and then the reflector $M_1$. However, it turns out that such a system is less effective and always leads to considerably higher losses (assuming again that the grating losses are dominant) and lower maximum values of $R_{\text{tot}}$. For reasons of comparison we also have calculated, for the case $g_0 L_{21} = 0.2$, the maximum output of such a configuration. The results are represented by the dotted lines of Fig. 3.

Next we calculate the ratio of the power $I_1$, leaving the active medium to the power $I_{\text{out}}$, impinging the grating. The derivation is straightforward and results in
Fig. 3. Maximum output power with corresponding values of $R_{21}$ as a function of $R_1$ for $g_{0L_1} = 0.2$. The dotted lines represent the output power if grating and mirror are interchanged.

$$\frac{I_{\text{grat}}}{I_1} = \frac{1 - R_1}{(1 + \sqrt{R_1} \sqrt{R_{21}})} \quad \text{(5)}$$

The calculated results in Fig. 4 show how much the exposure of the grating to high power is reduced as a consequence of the inserted mirror $M_1$. It is interesting to see that a small reflection on the inserted mirror already leads to a considerable reduction of the power impinging on the grating.

**Experimental Results**

With the described experimental setup we were able to tune continuously over all 65 transitions between $P(2)$ and $P(66)$ and between $R(0)$ and $R(62)$ of the $00^\circ 1-02^\circ 0$ vibrational mode, all 66 transitions between $P(2)$ and $P(68)$ and between $R(0)$ and $R(82)$ of the $00^\circ 1-10^\circ 0$ vibrational mode, and furthermore, 13 unidentified transitions between 11.0- and 11.3-μ wavelength presumably belonging to the $01^\circ 1-11^\circ 0$ vibrational mode. It should be noted that for low-power transitions $R_{\text{tot}}$ may be far above 90 percent in the absence of thermal deformations of the grating. This may explain that between 9.08- and 11.30-μ wavelength we found a total of 144 transitions with maximum spacing of 0.02 μ. Due to the poor power-handling capabilities of the grating and its increased reflectivity close to the blazed wavelength, it was not possible with this technique to obtain stable oscillations for the high-gain transitions of the $00^\circ 1-10^\circ 0$ mode. We shall come back to this problem at the end of the paper and propose another technique for the high-gain band. All other transitions were oscillating stably with maximum output powers up to 15 W in a large central region of the $00^\circ 1-02^\circ 0$ mode and a maximum of about 1 W for the $01^\circ 1-11^\circ 0$ mode. For the $R$ branch of the $00^\circ 1-02^\circ 0$ mode there is a region where the spacing between two transitions is not more than 0.008 μm. There, at one angular position, it was observed that two neighboring transitions may oscillate depending on the translational position scanning. They did not oscillate simultaneously, but apparently each one requires an $R_{\text{tot}}$ value above its minimum for oscillation. The latter depends of course on the gain of the transition and the cavity losses.

Figs. 5, 6, and 7 show the $R(10)$ and $R(12)$ transitions of the $00^\circ 1-02^\circ 0$ vibrational mode as a function of the position scanning of the piezoelectric translator. After a scan of a half-wavelength the output is repeated. The upper part shows the ramp voltage applied to the translator and the lower part the output both as a function of time. The oscillograms of Figs. 5 and 6 were obtained from the monochromator output. The oscillogram of Fig. 7 is a direct observation of the laser output beam. It is seen that, depending on the position of the translator, two transitions are observed but not at the same time. The traces were obtained by scanning the out-coupling cavity very slowly and the whole recorded graph was made in about 30 s. The intensities were measured by means of a thermopile having a time con-
Fig. 5. Oscillogram of R(10) transition obtained from the monochromator over a range of \( M_z \) travel. The upper part shows ramp voltage applied to the translator.

Fig. 6. Oscillogram of R(12) transition obtained from the monochromator over a range of \( M_z \) travel.

Fig. 7. Oscillogram of directly observed laser output over a range of \( M_z \) travel.

stant of about 20 ms. The asymmetry of the stronger line of Fig. 5 is related to a change of mode pattern from Gaussian to a low-order off-axis mode as the reflectivity decreases. This change in the mode pattern is easily demonstrated by illuminating a piece of asbestos with the laser beam. The strength of the relatively weaker line of Fig. 6 can be increased by changing the angular orientation, which was set to maximize the stronger line of Fig. 5.

DISCUSSION

The maximum reflectivity calculated according to (1) is limited by the condition that the reflectivity \( R_1 \) must be just below its minimum value for spontaneous oscillation of the strongest transitions. This maximum value of \( R_{\text{max}} \) is, however, not limited by absorption and scattering losses on the grating and can be increased if, for any system, the value of \( R_1 \) can be chosen higher. Thus, this technique can give high reflectivity (high Q values) at any selected wavelength and reduces considerably the power impinging on the grating.

So far we have been concerned with low gain transitions requiring high Q values and moderate radiation power. Due to the reduction of power impinging on the grating, the zeroth-order reflection may be used for outcoupling.

A different situation arises for the combination of high gain and high power as, for instance, with the central part of the 00'1-10'0 vibrational band. There the effective reflectivity for maximum output should be considerably below 100 percent. In such a case it is advantageous to use the present outcoupling device as a wavelength-selective end mirror with maximum reflectivity. It is seen from Fig. 4 that, for instance, a value of 90 percent for \( R_1 \) or more results in relatively very small values of \( I_{\text{out}} \) and therefore in negligibly small fractional losses. The effective reflectivity becomes 99 percent. Then the outcoupling may be achieved on the other side of the cavity by replacing the gold-coated end mirror of Fig. 1 with a partly transmitting dielectric mirror.

REFERENCES