Doctoral Thesis

Far infrared distributed-feedback gas laser

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FAR INFRARED DISTRIBUTED-FEEDBACK GAS LASER

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ABSTRACT

In this paper, experiments with the first distributed feedback (DFB) gas laser in operation are reported. A rectangular metallic waveguide with mechanically milled corrugations with a period of 248 μm is used. This produces efficient feedback at 496 μm, the emission wavelength of optically pumped Methylfluoride (CH₃F). This gas is chosen because it produce one of the strongest emission lines in the submillimeter region, and since its relatively large wavelength allows mechanical fabrication of the periodic structure.

The first section deals with the theory of a rectangular, metallic DFB waveguide. Starting with the theory of travelling wave tubes in the microwave region we calculate in particular the dispersion relation of a DFB waveguide. Based on these calculations we estimate the precision required for the manufacture of the periodic structure.

Construction of the waveguide and of the optically pumped CH₃F laser is described in section 2. The pump source is a transversely excited, single mode CO₂ laser. The temperature of the metallic waveguide can be varied between 0°C and 95°C.
Thus we obtain a tuning range for the period of $2 \cdot 10^{-3}$. Since the theory predicts a strong dependence of the laser characteristics on the waveguide height, this height can be varied between 0 and 20 mm.

Results on the experiments with the DFB laser are presented in section 3. In accordance with theory we found that laser emission only occurs when the polarization of the pump beam is parallel to the grooves of the periodic structure. Therefore, a TM mode propagates inside the waveguide. Furthermore, it is shown that only one transverse and longitudinal mode is excited and that the propagation of the beam is nearly diffraction limited. The spectral linewidth of less than 22 MHz is small enough for most applications of submillimeter lasers. The dependence of the output signal on the waveguide temperature and therefore on the period could be measured. Good agreement with theory was found.
ZUSAMMENFASSUNG


Im ersten Kapitel wird die Theorie eines metallischen, rechteckigen DFB Wellenleiters behandelt. Ausgehend von der Theorie der Wanderwellenröhren in der Mikrowellentechnik wird insbesondere die Dispersionsrelation des Wellenleiters berechnet. Dies ermöglicht dann eine Abschätzung der erforderlichen Präzision, mit der die periodische Struktur hergestellt werden muss.

Da die Theorie auch eine starke Abhängigkeit der Lasereigen-
schaffen von der Wellenleiterhöhe voraussagt, lässt sich diese
im Bereich von 0 bis 20 mm verstellen.

Im dritten Kapitel werden die experimentellen Ergebnisse
erläutert. In Übereinstimmung mit der Theorie hat sich gezeigt,
dass Laseremission nur auftritt, wenn die Polarisation des CO₂
Laserstrahls parallel zu den Furchen der periodischen Struktur
gerichtet ist. Im Wellenleiter wird also ein TM Mode angeregt.
Bei optisch gepumpten Submillimeter Lasern interessiert insbes-
sondere die spatiole und spektrale Zusammensetzung des Laser-
strahls. Es konnte gezeigt werden, dass der DFB Laser nur einen
einzigen transversalen und longitudinalen Mode emittiert, und
dass die Ausbreitung des Strahls annähernd beugungsbegrenzt
erfolgt. Die spektrale Linienbreite von weniger als 22 MHz
genügt für die weitaus meisten Anwendungen von Submillimeter
Lasern. Die Abhängigkeit des Ausgangssignals von der Wellen-
leitertemperatur und damit von der Periode konnte ebenfalls
nachgewiesen werden. Dabei wurde eine gute Übereinstimmung
mit der Theorie gefunden.
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INTRODUCTION

In 1971, Kogelnik and Shank demonstrated first operation of a distributed feedback (DFB) laser [1,2]. The active material was a gelatin film into which rhodamin 6G was dissolved. Soon after, the DFB configuration was applied to a semiconductor laser [3]. This device is of great interest in optical communication since it is well suited for integration.

Until today, application of the DFB principle remained restricted to dye and solid state lasers. These media exhibit a large gain bandwidth. Therefore, it is no serious problem to achieve coincidence between modulation period and emission wavelength. On the other hand, this coincidence is difficult to achieve in gases where the gain bandwidth is orders of magnitude smaller.

The first proposal of a hollow core DFB gas laser was made by Marcuse in 1972 [4]. He suggested the use of hollow dielectric waveguides with periodic ripples of the inner surface. Although these waveguides only support leaky modes, Marcuse could show that efficient operation of such a DFB laser should be possible. In 1978 and 1979 Miles and Grow published extensive calculations on the guiding properties
of dielectric DFB waveguides for CO\textsubscript{2} lasers [5,6]. They calculated a loss of 2.75 dB/m at 10.6 \textmu m for a waveguide made of BeO and glass and with a cross section of 0.1 mm x 2 mm.

In 1976 Yamanaka attempted the application of a periodic waveguide in a far-infrared optically pumped laser, as well as the construction of a monochromatic far-infrared source using a high pressure mercury lamp and a periodically corrugated waveguide as a narrow bandwidth backward-wave filter [7].

In this paper we report on experiments with the first DFB gas laser in operation [see also 8-11]. For this purpose we use a rectangular metallic waveguide with mechanically milled corrugations with a period of 248 \textmu m. This produces efficient feedback at 496 \textmu m, the emission wavelength of optically pumped CH\textsubscript{3}F. This gas is chosen because it produces one of the strongest emission lines in the submillimeter region, and since its relatively large wavelength allows mechanical fabrication of the periodic structure.

In section 1 of this paper we discuss the theory of a rectangular metallic DFB waveguide. Structures similar to the one incorporated in our laser are widely used in microwave travelling wave tubes for slowing down the electromagnetic wave in order to bring it into interaction with an electron beam. Consequently,
we started with the theory of these passive microwave devices [12] and introduced the active medium in the waveguide subsequently. This enabled us to calculate the dispersion relation and the threshold and resonance conditions. Based on these calculations we estimated the accuracy required for the manufacture of the periodic waveguide.

Construction of the waveguide and of the optically pumped CH₃F laser is described in section 2. Results on the experiments with our DFB laser are presented in section 3. The influence of the various waveguide and gas parameters on the emission are discussed, and the spatial and spectral characteristics of the output pulses are analyzed. Finally, the possibility of increasing the output energy as well as the application of a helical waveguide are discussed.

1. THEORY OF THE METALLIC PERIODIC WAVEGUIDE

1.1 Electric and magnetic fields of a TM mode

A cross section of the waveguide used in our experiment is shown in Fig. 1. It represents a parallel plate guide. Hence the electromagnetic fields are independent of the transverse coordinate x. According to Floquet's theorem the fields in
this type of periodic waveguide with propagation in the z-direction
can be written for \( y > 0 \) as [12]

\[
E_z(y, z) = \sum_{n=-\infty}^{\infty} E_{n0}(Ae^{i\beta_n z} + Be^{-i\beta_n z}) \sin[\tau_n(d-y)]
\]

\[
E_y(y, z) = -\sum_{n=-\infty}^{\infty} E_{n0} \tau_n (Ae^{i\beta_n z} - Be^{-i\beta_n z}) \cos[\tau_n(d-y)]
\]

\[
H_x(y, z) = -\sum_{n=-\infty}^{\infty} E_{n0} \tau_n (Ae^{i\beta_n z} + Be^{-i\beta_n z}) \cos[\tau_n(d-y)]
\]

where \( \beta_n = \beta_0 + 2\pi n/L \), \( \tau_n = \sqrt{k^2 - \beta_n^2} \), \( k = \omega/c \).

\( \beta_0 \) is the propagation constant.

In the slots we assume a standing wave in the y-direction:

\[
E_z(y) = \begin{cases} 
E_0 \frac{\sin[k(y+h)]}{\sin(kh)}(Ae^{i\beta_0 mL} + Be^{-i\beta_0 mL}) & \text{for } mL - \frac{\delta}{2} < z < mL + \frac{\delta}{2} \\
0 & \text{for } mL + \frac{\delta}{2} < z < (m+1)L - \frac{\delta}{2}
\end{cases}
\]

\[
E_y(y) = 0
\]

\[
H_x(y) = \begin{cases} 
iE_0 \frac{\cos[k(y+h)]}{\sin(kh)}(Ae^{i\beta_0 mL} + Be^{-i\beta_0 mL}) & \text{for } mL - \frac{\delta}{2} < z < mL + \frac{\delta}{2} \\
0 & \text{for } mL + \frac{\delta}{2} < z < (m+1)L - \frac{\delta}{2}
\end{cases}
\]

\( m \) is an integer.
The width of the slots is less than half the wavelength. Thus, the electric field exhibits no component in the y-direction. We also neglect the z-dependence of both the electric and the magnetic fields which is a good approximation for $\delta << L$.

Since the electric field in the slots has a component in the z-direction we expect a TM mode to oscillate in the waveguide. For this reason we have chosen the field statement according to (1).

1.2 Dispersion relation of the passive waveguide

In order to determine the dispersion relation $\beta_0(k)$ of our waveguide we first calculate the coefficients $E_{no}$ occurring in (1). Defining a scalar product

$$ (f,g) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(z) \cdot g(z) \, dz $$

we find the orthogonality relation

$$ (A e^{i\beta_m z} + B e^{-i\beta_m z}, A e^{i\beta_n z} + B e^{-i\beta_n z}) = (|A|^2 + |B|^2) \cdot \delta_{nm} $$

(4)
where \( \delta_{nm} = \begin{cases} 1 & \text{for } m = n \\ 0 & \text{for } m \neq n \end{cases} \).

With the aid of equation (4) we determine the coefficients.

\[
E_{no} = \frac{1}{|A|^2} \frac{1}{|B|^2} \frac{1}{\sin[\tau_n(d-y)]} \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} E(z)(A^*e^{-i\beta_n z} + B^*e^{i\beta_n z})dz
\]

(5)

Matching the electric field at the boundary \( y = 0 \) between the waveguide region and the slots results in

\[
E_{no} = \frac{1}{\sin(\tau_n d)} E_0 L \cdot \frac{\sin(\beta_n \delta/2)}{\beta_n \delta/2}.
\]

(6)

In a next step we have to match the magnetic field \( H_x \) for \( y = 0 \). Since we have neglected the \( z \)-dependence of the field components in the slots we can do that only approximatively.

We consider two different possibilities:

1) Matching the magnetic field in the centre of the slots \( z = m \cdot L \) leads to the following dispersion relation

\[
\frac{1}{kh \cdot \tan(kh)} = -\delta \sum_{n=-\infty}^{\infty} \frac{\cot(\tau_n d)}{\tau_n h} \cdot \frac{\sin(\beta_n \delta/2)}{\beta_n \delta/2}.
\]

(7)
II) Another possibility to match the magnetic field is to make 
the average value of the field in the waveguide equal to the 
field in the slots

\[ \frac{1}{\delta} \int_{mL-\delta/2}^{mL+\delta/2} H_{y>0} (z) \, dz = H_{y<0} \]

This leads to a somewhat different dispersion relation

\[ \frac{1}{kh \cdot \tan(kh)} = - \delta L \sum_{n=-\infty}^{\infty} \frac{\cotg(\gamma_n d)}{\gamma_n h} \left( \frac{\sin(\beta_n \delta/2)}{\beta_n \delta/2} \right)^2 \]  

Equation (7) is the dispersion relation given by Watkins [12]. 
Numerical calculations show that no significant difference 
exists between equations (7) and (8). Therefore, we shall 
consider only equation (7) in our further investigations.

1.3 Dispersion relation of the active waveguide

All the preceding formulas are derived under the assumption 
that no loss or gain exists inside the waveguide. In a distributed 
feedback laser, however, we have a net gain \( \alpha \) and, therefore, 
we have to modify our dispersion relation. Fortunately Butcher 
[13] has published a procedure to calculate the dispersion 
behaviour of a lossy periodic waveguide if the dispersion relation 
for the lossless guide is known. He showed that
\[ \omega(b) = \omega_x(b) \cdot (1 - \frac{i}{2Q_c}) \quad (9) \]

where \( \omega(b) \) : dispersion relation for a lossless guide \((\alpha=0)\)
\( \omega_x(b) \) : dispersion relation for a lossy guide \((\alpha \neq 0)\)
\( \beta \) : propagation constant
\( Q_c \) : Q-factor of the waveguide

We assume that the walls of the waveguide are perfectly conducting and that all the loss (or gain) is caused by the dielectric filling of the waveguide.

Butcher also calculated the Q-factor of the waveguide, which in our case is

\[ Q_c = -\frac{\omega_g}{2\alpha v_g} \quad (10) \]

Here \( v_g \) is the group velocity of the waveguide mode considered. In high gain media, such as CH$_3$F, the group velocity nearly equals c even in the Bragg region [14]. The deviation of \( v_g \) from c is calculated to be smaller than 1% for waveguide heights greater than 1.5 mm. Therefore we replace \( v_g \) by c in equation (10).
Equation (9) can therefore be written

\[ k(\beta) = k_x(\beta) + i\alpha \]  \hspace{1cm} (11)

assuming \( k = \frac{\omega}{c} \).

With relation (11) we can derive the dispersion relation \( \beta_0(k) \) of the active waveguide from equation (7):

\[
\frac{1}{(k+i\alpha)h \cdot \tan[(k+i\alpha)h]} = -\frac{\delta}{L} \sum_{n=-\infty}^{\infty} \frac{\text{ctg}(\tau_n d)}{\tau_n h} \cdot \frac{\sin(\beta_n \delta/2)}{\beta_n \delta/2}
\]  \hspace{1cm} (12)

with \( \tau_n = \sqrt{(k+i\alpha)^2 - \beta_n^2} \).

1.4 Resonance and threshold condition

In order to evaluate the resonance and threshold condition of a DFB laser, we consider a periodic waveguide of finite length \( R \). Outside the waveguide we assume a plane wave. By applying the condition of continuity at both ends \( z = \pm R/2 \) of the guide we find

\[
\sum_{n=-\infty}^{\infty} E_n \left[ \beta_n \cdot \cos\left(\frac{\beta_n R}{2}\right) + ik \cdot \sin\left(\frac{\beta_n R}{2}\right) \right] \cdot \]  \hspace{1cm} (13)

\[
\sum_{n=-\infty}^{\infty} E_n \left[ k \cdot \cos\left(\frac{\beta_n R}{2}\right) + i\beta_n \cdot \sin\left(\frac{\beta_n R}{2}\right) \right] = 0 \]  \hspace{1cm}.
Together with equations (6) and (12) we can calculate in principle the resonance frequencies $k_q$ and the corresponding threshold gain $\alpha_q$ of the longitudinal modes in our DFB laser.

1.5 Numerical results

Fig. 2 shows the results of a computer calculation of the dispersion relation (7) for a passive waveguide. As expected the cutoff frequency is the same as for a planar parallel plate guide with the same height $d$. Near the Bragg frequency the imaginary part of the propagation constant becomes negative and a stop band occurs. This means that the amplitude of a propagating wave shows an exponential decay and that the wave is reflected back. This behaviour is quite similar to that of electrons moving in a periodic potential. There, the waves are known as Bloch waves.

A further interesting detail is the shift of the band gap relative to the Bragg frequency. This corresponds to a change in the average phase velocity and it is also observed in dielectric periodic waveguides [15].
If we introduce a gain \( \alpha \) the dispersion relation alters completely (Fig. 3). The band gap disappears and the imaginary part of the propagation constant exhibits a positive resonance. It is in the region of this resonance where we will operate our DFB laser.

In Figs. 2 and 3 we have only plotted the lowest mode. The curves for the higher modes are quite similar but shifted towards higher frequencies.

Distributed feedback was previously used in semiconductor and in dye lasers. Typically these media have a relative gain bandwidth between 1 and 10 percent [16]. This value determines the precision needed for the manufacture of the periodic structure and can be achieved without problems. Closer tolerances have to be met only if one requires a well defined emission wavelength.

If the active medium in a DFB laser is a gas the relative gain bandwidth is narrow. For pulsed CO\(_2\) as well as for optically pumped CH\(_3\)F lasers it is only in the order of \(10^{-4}\). It is therefore of special interest to know the bandwidth \(\Delta k\) of the Bragg region with efficient feedback. Fig. 4 shows the relative bandwidth \(\Delta k/k\) of the band gap as a function of the ratio \(d/L\) for the two lowest modes. \(\Delta k/k\) is approximately proportional to \(1/d^2\).
Since the right hand side of equation (12) is a very slowly converging sum, numerical calculations of the dispersion relation are rather time consuming. For this reason we tried to find an approximative solution for the relative bandwidth. Taking only the terms with n = 0 and n = -1 in equation (12) and putting $\beta_0 = \pi/L$ we obtain for $\alpha = 0$

\[
\frac{1}{k \cdot \tan(kh)} + \frac{2\delta \sin(\pi \delta)}{L} \frac{\sin(\frac{\pi \delta}{2})}{\frac{\pi \delta}{2}} \frac{1}{\sqrt{k^2 - \frac{2}{\pi^2}} \cdot \tan(\sqrt{k^2 - \frac{2}{\pi^2}} d)} = 0 .
\]

The first zero $k_0$ of this equation gives us the bandwidth $k = k_0 - \pi/L$ for the lowest mode. The dotted line in Fig. 4 is a result of this approximation. The agreement with the precise curve is excellent for $d/L < 100$.

A further figure of merit is the maximum of the imaginary part of the propagation constant inside the stopband. This represents a measure for the strength of the feedback. As indicated in Fig. 5 the feedback decreases with the square of the waveguide height.

From the preceding calculations it seems advantageous to take the waveguide height as small as possible. On the other hand there are two effects which favour a large waveguide height. First, we should have a large gas volume to obtain high output.
energies. Second, the waveguide losses increase with decreasing diameter $d$. The wall losses of the lowest TM mode in a planar parallel plate guide are given by [17]

$$\alpha_{TM} = -\frac{2}{d} \frac{R}{Z_0} \frac{1}{\sqrt{1-\left(\frac{\lambda}{2d}\right)^2}} \tag{15}$$

where $R$ is the surface impedance of the metallic walls and $Z_0 = 377 \, \Omega$. In Fig. 6 we plot the wall losses for the $TM_{01}$-mode (also called $E_{01}$-mode) in a brass waveguide at a wavelength of 496 $\mu$m.

From the above analysis we expect an optimum waveguide height which depends on the gain of the laser medium and on the waveguide material.

1.6 Coupled-wave theory of waveguide DFB lasers

The approximations in section 1.5 have shown that the consideration of only the lowest terms in (12) results in a good agreement with the exact calculations. This means that the coupled-wave theory of Kogelnik and Shank [14] also gives an adequate description of our DFB laser. In particular we can calculate the longitudinal mode spacing of the DFB laser.
Equation (27) in Ref. 14 can be written as

\[ \frac{2}{\lambda_g} = \frac{1}{L} + \frac{1}{R}(q + \frac{1}{2}) \quad \text{, \quad q integer} \]  

(16)

where \( \lambda_g \) is the wavelength in the waveguide. If we introduce the number \( M = R/L \) of periodic corrugations we can transform equation (16) into a more convenient form

\[ R = \frac{\lambda_g}{2}(M + q + \frac{1}{2}) \]  

(17)

This resonance condition differs from that of a plane Fabry-Perot resonator only by a phase shift of \( \lambda_g/4 \) which is not important. The relevant difference between DFB modes and Fabry-Perot modes is the increasing threshold gain with increasing mode number \(|q|\) in a DFB laser.

For a metallic waveguide the guide wavelength \( \lambda_g \) is

\[ \lambda_g = \lambda[1 - (\lambda/\lambda_c)^2]^{-\frac{1}{2}} \]  

(18)

\( \lambda_c \) is the cutoff wavelength. The refractive index of the laser gas is assumed to be equal to 1. In a rectangular guide of width \( a \) and height \( d \) the cutoff wavelength \( \lambda_{c, \text{nm}} \) is given by
\[ \lambda_{c, nm} = 2 \left[ \left( \frac{m}{a} \right)^2 + \left( \frac{n}{d} \right)^2 \right]^{-1/2} \]  

The subscripts \( n \) and \( m \) denote the transverse modes. In our waveguide is \( a \gg d \). The resonance condition (17) can therefore be written

\[ R_{qn} = \frac{\lambda}{2} \left[ 1 - \left( \frac{\lambda}{2} \right)^2 \left( \frac{n}{d} \right)^2 \right]^{-1/2} \cdot (M + q + \frac{1}{2}) \]

With the aid of this equation we can calculate the longitudinal mode spacing. We notice that this spacing is greater than \( \lambda/2 \).

2. CONSTRUCTION OF THE LASER

The design of the DFB laser is based on the calculations in section 1. Fig. 7 shows a schematic diagram of the experimental setup. The active laser medium is \( \text{CH}_3\text{F} \), optically pumped by the 9P(20) line of a grating tuned single mode CO\(_2\) laser. The maximum available pump energy is one Joule which allows power densities of several MW/cm\(^2\). The pump beam is adapted to the waveguide by a condensing telescope with either circular or cylindrical lenses.
The waveguide for the far infrared (FIR) radiation consists of the periodic structure at the bottom and three plane metallic walls. Although the rectangular metallic waveguide exhibits remarkable losses in the FIR we have chosen this configuration. It is easy to manufacture and exhibits good polarization characteristics [18]. In our experiment we usually pump only a fraction of the whole waveguide. Consequently it acts more as a parallel plate guide than as a rectangular guide.

Fig. 8 shows the corrugated wall of the DFB waveguide with a length of 32 cm. According to equation (20) the period of the structure should be close to half the wavelength. For the dominant emission line of CH$_3$F this corresponds to a period of 248.05 µm. The allowed deviation from this value is determined by the width of the band gap in the dispersion relation. According to Fig. 4 this bandwidth is only $8 \times 10^{-4}$ for a waveguide height of 3 mm and becomes even smaller for greater diameters. For this reason we incorporated a temperature control which allows a temperature variation of the waveguide between $-32^\circ C$ and $95^\circ C$. Thus the period of our structure can be tuned by a factor of about $2 \times 10^{-3}$ which corresponds to 0.5 µm.
We have measured the period of the structure at room temperature by means of a projecting microscope with a reading precision of one micron. In order to increase the accuracy of measurement we measured 100 periods and determined an average value for the period. Our result was $L = 247.99 \pm 0.02 \, \mu m$ instead of the desired $248.05 \, \mu m$. This corresponds to a relative deviation of only $2.4 \times 10^{-4}$ which lies well within our tuning range. It should be noted that the determination of an average value for the period is reasonable since small statistical deviations from the correct period cause no significant alteration in the DFB characteristics of the waveguide [19].

The depth of the corrugations is $124 \, \mu m$, a quarter of the emitted wavelength. In general it should be an odd multiple of $\lambda/4$. If the depth is an even multiple of $\lambda/4$ the standing wave (2) has a node at the boundary between the slots and the guiding region and the structure acts like a homogeneous waveguide.

As we have seen the waveguide properties depend strongly on the height $d$. In our laser this height is adjustable between 0 and 20 mm.
In table I we give a summary of the characteristics of our DFB laser. For the calculations of the gain bandwidth in CH$_3$F we have neglected Raman contributions [20, 21].

3. EXPERIMENTAL RESULTS

3.1 Transmission characteristics of the passive waveguide

The transmissivity and reflectivity of DFB waveguides in the visible or near infrared are normally measured with a dye laser. Since no tunable source is available in our wavelength region we have taken a common optically pumped CH$_3$F laser. Instead of tuning the wavelength we have varied the temperature and therefore the period of the waveguide and monitored the transmitted signal during the heating cycle.

Fig. 9 shows the measured transmissivity for two different diameters of the waveguide. The polarization of the laser beam is perpendicular to the grooves. We observe a remarkable decrease in the transmitted signal for temperatures above 40°C. The width $\Delta T$ of this resonances can be converted into a corresponding bandwidth $\Delta \lambda$. The measured bandwidth, shown in Fig. 10, depends on the waveguide height $d$. For an infinitely long waveguide a lower limit for $\Delta \lambda$ can be taken from Fig. 4.
Variations in the grating period and in the guide height $d$ cause an increase of the bandwidth [22].

For a waveguide of finite length $R$ the bandwidth will be further enlarged. For weak coupling we can give a rough estimate for $\Delta \lambda$ from Ref. 23.

$$\frac{\Delta \lambda}{\lambda} \gtrsim \frac{L}{R} = \frac{1}{M}$$

(21)

where $L$ is the grating period and $M$ is the number of grooves.

For our waveguide where $L = 248 \, \mu m$ and $R = 32 \, cm$ we obtain $\Delta \lambda \gtrsim 0.19 \, \mu m$. The condition of weak coupling implies a transmissivity near 1 at the Bragg frequency and is met in our configuration only for diameters $d \gtrsim 3 \, mm$. For greater waveguide heights the transmission remains close to 100% even at the Bragg resonance. For the determination of the bandwidth at these diameters it is favourable to measure the reflectivity of the structure. But since we can not suppress completely the reflections from the front end of the guide and due to pulse to pulse fluctuations in the laser output precise measurements are not possible.
3.2 Dependence of the laser output on the waveguide period

The results of the preceding section demonstrate that our waveguide shows a distributed feedback. Laser action can be expected if we overcome the threshold for the given length of the structure. In the subsequent experiment we have pumped the waveguide with the single mode output of a CO$_2$ laser at an intensity of 23 MW/cm$^2$. This is the intensity measured at the input of the glass tube which contains the DFB laser. Due to the construction of our laser the pump beam first passes a distance of about 30 cm in the tube before entering the waveguide. This reduces the power by about 35% at typical operating pressures of 5 - 6 torr. Therefore, we have an effective pump intensity of 15 MW/cm$^2$. At this power level the absorption is highly saturated [24].

The pulse energy measured with a Golay detector is shown in Fig. 11 as a function of the waveguide temperature for a height of about 2.5 mm. Below 30°C we observe a constant pulse energy. This signal is caused by superradiant emission which does not depend on the waveguide period. When the temperature is increased we observe a resonance located at 55°C. This resonance clearly shows the resonator effect in our waveguide. The halfwidth of the peak is 27 K. It is difficult to give a value for the expected bandwidth since we have to take into account the possibility of Raman contributions to the gain. At the high pump intensities used in our experiment a significant part
of the emission is expected to be of this type [20, 21]. In addition, with a high power pump laser several K levels can be excited and this will also cause an increase of the gain bandwidth [25, 26].

When the waveguide height is fixed at 2 mm we observe two peaks when our waveguide length is tuned by temperature variation (Fig. 12). The separation of the two peaks is about 40 K. From equation (20) we calculate the spacing of two longitudinal modes. For $\lambda = 496 \ \mu m$, $d = 2 \ mm$ and $n = 1$ we obtain

$$\Delta R(\Delta q=1, \Delta n=0) = 250 \ \mu m$$

This value corresponds to a relative length change of $7.8 \cdot 10^{-4}$. The thermal coefficient of expansion for brass is $1.85 \cdot 10^{-5} \ K^{-1}$. With these values we calculate a longitudinal mode spacing of 42 K in good agreement with the measured value of 40 K.

DFB theory also predicts different thresholds for the longitudinal modes. This can be also observed in Fig. 12. When we pump the laser with an energy of 320 mJ, corresponding to 14 MW/cm$^2$, we observe only one mode compared to the two modes for a pump energy of 550 mJ. Since the threshold increases with increasing deviation from the Bragg frequency we conclude that our DFB laser operates on the high frequency side of the stop band. This will be of interest in the discussion of optimizing our waveguide.
Because the ground-state population of the lasing molecule is sensitive to temperature the output power of all optically pumped gas lasers varies with temperature. In CH$_3$F we expect a decreasing pulse energy when the temperature is raised over room temperature. Walzer and Tacke [27] observed a decrease of about 50% between 40°C and 80°C in cw operation. Thus, the effect of different thresholds for various longitudinal modes is even stronger than indicated in Fig. 12.

As we see in Figs. 11 and 12 the location of the peaks depends on the waveguide height. This can be explained by a simple consideration. An increase of the height d decreases the transverse wavenumber $\frac{n\pi}{d}$. This leads to an increase of the longitudinal wavenumber $\frac{2\pi}{\lambda g}$ since

$$
\left(\frac{n\pi}{d}\right)^2 + \left(\frac{2\pi}{\lambda g}\right)^2 = \left(\frac{2\pi}{\lambda}\right)^2
$$

(22)

A greater longitudinal wavenumber means a shorter wavelength in the guide and therefore a shift of the peak in Fig. 11 to lower temperatures. This is observed when the waveguide diameter is varied between 1.75 and 2.5 mm (Fig. 13). The values of d in Fig. 13 are accurate to 1/100 mm only with respect to the reference height d = 2.00 mm. The absolute precision is ±0.1 mm.
In order to prove DFB operation of the laser care has to be taken to avoid reflections from the ends of the waveguide. The impedance mismatch and therefore the reflection coefficient is expected to be high for higher order transverse modes. We were able to confirm DFB operation by replacing the corrugated waveguide wall by a plane metal plate. As a consequence of this replacement the laser emission disappeared.

As already mentioned in section 1.1 we expect a TM mode to oscillate in our waveguide. For this reason we choose the polarization of the pump beam parallel to the grooves. The output beam is then polarized perpendicular to the grooves. The degree of polarization is greater than 97% which is the limiting value of our polarizer. When we rotate the polarization of the pump beam by 90° no output is observed although the losses for TE modes in a parallel plate guide are smaller than for TM modes. This shows that the field statements (1) in section 1.1 are correct.

The emitted energy was also found to depend strongly on the waveguide height. When the pulse energy is plotted as a function of the waveguide diameter d several irregular peaks appear. The location and width of these peaks depend on the waveguide temperature but no systematic behaviour can be found.
The highest output energies were measured at temperatures above 70°C. As already mentioned in section 1.5 we expect a limited range for the waveguide height where lasing is possible. This could be verified. For diameters approximately below 1 mm and above 2.7 mm laser action ceased completely.

3.3 Pressure dependence of the laser output

In Fig. 14 we plot the pressure dependence of the output signal for three different pump intensities. The optimum pressure lies between 4 and 7 torr. This is several times higher than for conventional optically pumped CH$_3$F lasers [28, 29]. The reason for these high optimum pressures is the very short cavity length of only 32 cm. Plant et al. [30] have shown that the optimum cell pressure increases when the resonator length is reduced. Operating pressures exceeding 20 torr were found for a 39 cm long, unstable resonator pumped with a CO$_2$ energy of 1.14 Joule [31].

3.4 Spatial and spectral characteristics of the laser output

The transverse energy distributions of the output beam were measured by scanning a Golay cell with a 1.5 mm diameter diaphragm across the beam profile. The horizontal and vertical field distributions are given in Figs. 15 and 16 for a temperature of 74°C and a waveguide height of 2.13 mm. Measurements were made at a distance of 150 mm from the end of the waveguide.
The single peaks in both directions indicate mode numbers $n = m = 1$ in equation (19).

The fact that only the lowest order mode exists once again proves that reflections from the waveguide ends can be neglected. The power reflection coefficient for the lowest order TM mode is

$$r = \frac{\sqrt{1 - \left(\frac{\lambda}{2d}\right)^2} - 1}{\sqrt{1 - \left(\frac{\lambda}{2d}\right)^2} + 1}. \quad (23)$$

A waveguide height $d$ of 2.1 mm leads to a reflection coefficient $r = 1.2 \times 10^{-5}$ which is orders of magnitude too small for laser action.

The beam divergence in both directions was calculated from the field distributions measured at various distances from the waveguide end. We found for the full angle divergence in the horizontal plane a value of 38 mrad which is nearly diffraction limited. The divergence in the vertical direction depends on the waveguide height and was found to be diffraction limited too.
The wavelength and the spectral content of the submillimeter radiation were measured with the aid of a scanning Fabry-Perot interferometer. The plate spacing was set to 30.5 cm, giving a free spectral range of 492 MHz. The grating constant of the meshes was 63.5 μm and the measured finesse was 22. A typical interferogram is shown in Fig. 17. The wavelength is found to be 496 μm as expected. We observe a strongly dominant mode in agreement with the measurements of the transverse field distributions in Figs. 15 and 16. The full width at half maximum of the dominant mode is about 22 MHz, a value which corresponds to the spectral resolution of the interferometer.

Since the temperature of the waveguide determines the exact period a temperature change should result in an alteration of the emission frequency. This is shown in Fig. 18 for a waveguide height of 2.5 mm. The reduction in the finesse compared to the interferogram in Fig. 17 is probably caused by a slight misalignment of the meshes. In Fig. 19 we plot the displacement of the dominant mode as a function of the waveguide temperature. The point at room temperature was taken as a reference. The straight line is a least square fit to the experimental points. Its slope is about 2.3 MHz/K. A theoretical calculation gives a value about a factor of five higher. The reason for this discrepancy is the assumption of a constant waveguide height for all temperatures. In our
configuration this is not true, but due to the construction of the height adjustment it is not possible to give a precise value for the alteration.

The strong dependence of the emission frequency on waveguide temperature offers a simple possibility of frequency stabilization of the DFB laser. A temperature stability of 0.1 K which is relatively simple to achieve keeps the frequency within 230 kHz or $4 \times 10^{-7}$. This is a good value for a passive stabilization. It could be interesting for a cw source used as a local oscillator in a heterodyne experiment.

3.5 Output energy and pulse shape

We have measured the output energy with a pyroelectric Joulemeter (Molelectron J3-05). The uncorrected reading corresponds to an energy of 2 μJ when pumped with a single mode pulse. Pumping with the multimode output of the CO₂ laser leads to an energy about a factor of five higher but the shot to shot fluctuations also increase.

Studies of the temporal behaviour of the pulses were performed using a photon drag detector for the CO₂ beam and a Schottky barrier diode for the submillimeter (SMM) beam. Fig. 20 shows the time resolved shapes of the pump and SMM pulses for 5.5 torr CH₃F pressure. The pulsewidth of the CH₃F pulse is about 50 ns.
This corresponds to a minimum linewidth of 20 MHz which is slightly less than the value observed in Fig. 17. Together with the output energy of 2 μJ we calculate a peak power of about 40 Watts.

4. CONCLUSIONS

We have calculated the dispersion relation and the threshold and resonance condition of a hollow, periodically corrugated waveguide for application in optically pumped submillimeter lasers. Based on these calculations we have built and operated the first DFB gas laser. It is shown that the laser operates in a single longitudinal and transverse mode. The divergence of the output beam is found to be diffraction limited in both the horizontal and the vertical plane. A spectral linewidth of less than 22 MHz is measured which is small enough for most applications of FIR lasers. The temperature tuning curves show that frequency stabilization of the DFB laser can be achieved by a simple control of the temperature of the waveguide. The pulse width is about 50 ns.

Since we also expected successful operation of our DFB laser for waveguide heights larger than 3 mm we have chosen a corrugation period of exact half the wavelength. Yet for small waveguide diameters the optimum period is slightly more than half the wavelength. For a waveguide height of 2 mm we find a period
of 249.9 \mu\text{m}. Our next experiments will be performed with a structure period of 250 \mu\text{m}. This should result in lower threshold pump powers and higher output energies.

The measured pulse energy is a few microjoules. Low output energies were expected due to the small waveguide height of less than 3 mm and the short cavity length of 32 cm. Higher output energies can be achieved by a modification of the DFB laser. Instead of using the corrugated waveguide as the active laser structure it could be used as a partially reflecting "mirror" in a conventional optically pumped laser. This would permit longer waveguides and therefore result in higher pulse energies. Such a configuration is known as distributed Bragg reflector (DBR) laser. In optically pumped lasers it would render unnecessary hole or hybrid output mirrors since the corrugated waveguide is highly transparent for the pump radiation. A further advantage is the possibility of temperature tuning the reflectivity and therefore optimizing the output coupling.
A further improvement of the optically pumped DFB laser could result when the manufacture of a circular DFB waveguide is possible. Another solution may be found in the form of an oversized helical waveguide [33]. These waveguides are widely used in microwave travelling wave tubes and should be simpler to manufacture than a circular DFB structure. Experiments with helical waveguides are under way in our laboratory.
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REFERENCES


### TABLE I

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Gain bandwidth ($p = 5$ torr)</td>
<td>$3 \cdot 10^{-4}$ (200 MHz)</td>
</tr>
<tr>
<td>Band gap ($d = 3$ mm)</td>
<td>$8 \cdot 10^{-4}$ (480 MHz)</td>
</tr>
<tr>
<td>Longitudinal mode spacing</td>
<td>$8 \cdot 10^{-4}$ (470 MHz)</td>
</tr>
<tr>
<td>Waveguide tuning ($\Delta T = 100$ K)</td>
<td>$1.8 \cdot 10^{-3}$ (1100 MHz)</td>
</tr>
<tr>
<td>Measured difference between Waveguide period and $\lambda/2$</td>
<td>$2.4 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Characteristics of the DFB CH$_3$F laser. For the calculation of the gain bandwidth Raman contributions are neglected.
FIGURE CAPTIONS

FIG. 1 Cross section of the DFB waveguide.

FIG. 2 Dispersion relation for a passive ($\alpha=0$) DFB waveguide.

FIG. 3 Dispersion relation for a DFB waveguide with gain ($\alpha>0$).

FIG. 4 Relative bandwidth $\Delta k/k$ of the stop band as a function of the waveguide height $d$. The dotted line is an approximation for the dominant mode according to (14). $\delta/L$ was assumed 0.2.

FIG. 5 Maximum of the imaginary part of the propagation constant vs waveguide height $d$. $\text{Im}(\beta_0)_{\text{max}}$ is a measure for the strength of the feedback.

FIG. 6 Wall losses for the $TM_{01}$ (or $E_{01}$) mode in a metallic parallel plate waveguide at a wavelength of 496 $\mu$m.

FIG. 7 Experimental arrangement. The DFB waveguide is rotated by $90^\circ$ for clarity.
FIG. 8 Periodic structure used in the DFB laser. The mean period is $247.99 \pm 0.02 \, \mu m$ corresponding to half the wavelength of the optically pumped CH$_3$F emission.

FIG. 9 Transmissivity of the DFB waveguide for various diameters. The transmissivity at room temperature is normalized to one.

FIG. 10 Measured bandwidth $\Delta \lambda$ of the stop band vs waveguide height $d$. The waveguide length is 32 cm.

FIG. 11 Output energy as a function of the waveguide temperature $T$. The active pump intensity is 15 MW/cm$^2$ and the waveguide diameter is about 2.5 mm. Error bars indicate pulse to pulse fluctuations.

FIG. 12 Output energy as a function of the waveguide temperature $T$ for a diameter $d = 2 \, \text{mm}$. Two longitudinal modes with different thresholds are observed.

FIG. 13 Output energy vs waveguide temperature for various waveguide diameters. The values of $d$ are accurate to 1/100 mm only with respect to the reference height $d = 2.00 \, \text{mm}$.
FIG. 14 Pressure dependence of the Golay signal for three different pump intensities. The indicated pump intensities are measured at the input window of the glass tube and must be reduced by about 35\% to obtain the intensities reaching the DFB waveguide.

FIG. 15 Transverse mode pattern in horizontal direction measured at a distance of 15 cm from the waveguide end.

FIG. 16 Transverse mode pattern in vertical direction measured at a distance of 15 cm from the waveguide end.

FIG. 17 Fabry-Perot interferogram of the DFB laser emission. The linewidth is limited by the spectral resolution of the interferometer.

FIG. 18 Fabry-Perot interferograms of the laser emission at various waveguide temperatures. The waveguide height is 2.5 mm.

FIG. 19 Frequency shift of the laser emission vs waveguide temperature. The point at room temperature was taken as a reference.

FIG. 20 Temporal shape of the CO$_2$ (upper) and CH$_3$F (lower) pulses. The CH$_3$F cavity pressure was 5.5 torr.
Fig. 5

$\text{Im}(\beta_0)_{\text{max}} \cdot L$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$d/L$

1st mode

2nd mode
$\alpha \text{ (m}^{-1}\text{)}$ vs $d \text{ (mm)}$

$R = 0.39 \Omega \ (\text{Brass, } \lambda = 496 \mu\text{m})$
Fig. 10

\[ \Delta \lambda (\mu m) \]

\[ d (mm) \]

- 0.34
- 0.2
- 0.1

Graph showing the relationship between \( \Delta \lambda \) and \( d \).
p = 6 Torr

$E_{PUMP} = 550 \text{ mJ}$
Fig. 12

Pulse Energy (arbitrary units)

Temperature (°C)

- \( p = 4.5 \) Torr
  \( E_{\text{PUMP}} = 320 \) mJ
- \( \Delta p = 4 \) Torr
  \( E_{\text{PUMP}} = 210 \) mJ
Fig. 14
horizontal

d = 2.13 mm

T = 74°C
vertical
d = 2.13 mm
T = 74°C
Fig. 17

d = 2.3 mm
T = 75°C
Fig. 19

- $\Delta v$ (MHz)

$T$ (°C)

2.29 MHz/K
Fig. 20

Intensity (arb. units)

CO$_2$

CH$_3$F

50 ns/div
CURRICULUM VITAE

I was born in Lucerne, canton Lucerne, on the 11th May 1951 as a citizen of Leuzigen BE. I attended the primary school in Kriens LU until autumn 1963. After seven years at the Cantonal High School in Lucerne I passed the examination "Maturität Typus C" in summer 1970 and entered the Department of Mathematics and Physics of the Swiss Federal Institute of Technology in Zurich. In spring 1975 I received the diploma of physics with my work on "Monomolecular Optical Layers". Since May 1975 I worked under the guidance of Professor Kneubühl at the Solid State Physics Laboratory of the Swiss Federal Institute of Technology Zurich, where I was engaged in the research of submillimeter gas lasers.