High Power Optically Pumped Far Infrared Laser Systems

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Abstract—Single mode, 60-80 ns pulse width, 50-70 kW peak power laser oscillators operating on the 384.6 µm line of D₂O have been developed. The characteristic linewidths of these oscillators are less than 25 MHz full width at half maximum which favorably compares with the intrinsic width of 6-8 MHz associated with the pulse length of about 60 ns. A 12.7 mJ, 195 kW, 384.6 µm D₂O laser oscillator-amplifier combination has been constructed and tested. Although single longitudinal mode operation is attained from this oscillator-proposed [1], the amplifier adds low power level wide-bandwidth background radiation. Amplified spontaneous emission (superradiance) from the amplifier adds low power level wide-bandwidth background radiation. Studies of far infrared lasing action in CH₃F and CH₃I are also described.

The potential application of high power narrow linewidth far infrared radiation (FIR) for determination of ion temperature in tokamak plasmas by Thomson scattering was proposed [1], [2] after the first demonstration of optically pumped laser action in CH₃F [3] and the subsequent production of higher power outputs from mirrorless lasers [4], [5]. At present it appears that power levels on the order of 1 MW, pulse energies on the order of 200 mJ, and full linewidth of 20-40 MHz between 10 dB points are required. Also full widths of less than 100 MHz at the 30 dB and 200 MHz at the 50 dB points are required for Thomson scattering measurements of tokamak plasmas and other hot plasmas with electron densities of about 10¹⁴ cm⁻³. In this paper we discuss various means of achieving high power, narrow linewidth output from a FIR laser system.

Attempts have been made to generate high power narrow linewidth radiation in CH₃F by pumping it with the 9.55 µm P(20) line of high power pulsed CO₂ lasers. Reasonably good power conversion efficiencies were obtained in amplified spontaneous emission (ASE) type lasers [6]-[10]. A variety of linewidths were reported for these lasers, all of them in the range from 300 MHz to 700 MHz FWHM. Such large linewidth was attributed to the possibility of simultaneous pumping, due to the off resonant pumping effect [11], of a number of rotational K-sublevels of the J = 12 rotational level of CH₃F. These levels can then lase simultaneously, giving a frequency spread of (K₃² - K₉²) X 13 MHz. To overcome the linewidth problems various oscillators were constructed [12]-[14]. All of them provided narrow linewidth outputs on a number of longitudinal or transverse modes. To increase the power, oscillator-amplifier assemblies were constructed [15]-[18], [10]. All of the published scanning Fabry-Perot interferograms of the outputs of these systems exhibit similar shape: a relatively narrow central peak resting on a broad base of ASE arising from the amplifier. Our highest power CH₃F oscillator-amplifier system, sketched in Fig. 1, clearly exhibited this type of behavior, as shown in Fig. 2. This system consisted of a 1.25 m long oscillator and a 2.8 m long amplifier pumped by 20 and 80 percent of a 200 MW CO₂ laser output, respectively. The maximum output on the 496 µm line was 130 kW peak power in a 60 ns FWHM pulse and was achieved at a CH₃F pressure of 3 torr in both the oscillator and the amplifier. Our FIR energy measurements were performed using a Laser Precision RkP-335, 1 cm² area pyroelectric detector with an extended spectral response coating. The time evolution of the pulses was observed with a Schottky diode detector.

The linewidth quality can be significantly improved by pursuing two new directions: 1) employing a lasing medium with only one level excited by the pump radiation and 2) by developing a single mode cavity with a very high power output, thus placing far less reliance upon a very high gain amplifier section. The results of these attempts are described below.

A preliminary search indicated promising results for the 447 µm line of CH₃I. The 10.57 µm P(18) line of CO₂ resonantly pumps the R₉(44) transition of the ν₆ bending mode and the 447 µm lasing transition is 0P₆(45) [19]-[22]. Only one CH₃I level is pumped, the other allowed pump transitions being separated by large frequency differences. The spectral width of the output of a 3 m long ASE type laser operating with CH₃I was measured to be 100 MHz FWHM [23] which is quite narrow when compared with the CH₃F [6]-[10] and D₂O [24] results. The energy output from the CH₃I gas in all our laser systems was always at least a factor of 10 below the output from CH₃F or D₂O in the same systems. We explain this low energy output by the very low population level at
room temperature of the \((v_2 = 0, J = 44, K = 5)\) level of \(\text{CH}_3\text{I}\). Only about 0.07 percent of all of the \(\text{CH}_3\text{I}\) molecules lie in this level as compared to about 1.8 percent for the \(5_{23}\) level of \(\text{D}_2\text{O}\) and about 4 percent for the \(K = 1\) to \(K = 6\) sublevels of the \(J = 12\) level of \(\text{CH}_3\text{F}\) [25].

A narrow linewidth output is not the only laser requirement for plasma diagnostics. High power is also necessary and therefore we have concentrated our efforts on \(\text{CH}_3\text{F}\) and \(\text{D}_2\text{O}\). \(\text{D}_2\text{O}\) has proven to provide up to three times more output than \(\text{CH}_3\text{F}\) in similar systems. This can be attributed to the fact that, disregarding cascade and refilling lines, \(\text{D}_2\text{O}\) has only one lasing transition, while \(\text{CH}_3\text{F}\), because of its closely spaced K sublevels, has 5–7 transitions, only one of which can be in resonance with a single mode cavity. The other \(\text{CH}_3\text{F}\) transitions lase less efficiently because they are very far off resonance [26]. Furthermore, for ion Thomson scattering in a tokamak, the 384.6 \(\mu\)m line of \(\text{D}_2\text{O}\) may be better suited than the 496 \(\mu\)m line of \(\text{CH}_3\text{F}\) because it is further away from the radiation of the low-order harmonics of the cyclotron frequency for the high magnetic field tokamaks [27].

The advantages of \(\text{D}_2\text{O}\) caused us to concentrate our effort on the development of a suitable \(\text{D}_2\text{O}\) laser system. Following the description of the \(\text{D}_2\text{O}\) levels participating in the laser action we will describe the four distinct laser systems we have built and tested. These were an oscillator-amplifier system, a mode injection system, a high power short oscillator, and a high power long oscillator with an interferometric mode selector.

Fig. 3 shows the level diagram of the \(\text{D}_2\text{O}\) laser. The 9.26 \(\mu\)m \(R(22)\) line of the \(\text{CO}_2\) laser pumps the \((v_2 = 0, 5_{23})\) to \((v_2 = 1, 4_{22})\) transition in \(\text{D}_2\text{O}\), the center of the \(\text{CO}_2\) line being offset from the center of the \(\text{D}_2\text{O}\) transition by \(-318\) MHz [28]. The lasing occurs on the \(4_{23}\) to \(4_{13}\) transition at 384.6 \(\mu\)m ± 0.5 \(\mu\)m [24], [28]–[30] and on a cascade \(4_{13}\) to \(4_{04}\) transition at 359.3 \(\mu\)m ± 0.5 \(\mu\)m [24], [29]–[30]. Our highest power system [24] consisted of a short 0.36 m oscillator pumped by 20 percent of the \(\text{CO}_2\) beam and an 8 m long amplifier pumped by the remaining 80 percent of the \(\text{CO}_2\) beam. A quartz crystal at 45° angle acted as a transmitter for the FIR beam and a reflector for \(\text{CO}_2\) [31] in the amplifier. This system produced 195 kW pulses, 70 MHz FWHM, at 384.6 \(\mu\)m at the \(\text{D}_2\text{O}\) pressure of 5.5 torr in the oscillator and 4.0 torr in the amplifier. The spectral output also showed the presence of the 359.3 \(\mu\)m line and a broad background of ASE from the amplifier. The breadth of the ASE output, 450 MHz FWHM [24], was much larger than could be expected from the homogeneous pressure broadening of the FIR transition. This broadening of 26 MHz FWHM torr\(^{-1}\) [28] should have produced only 100–130 MHz linewidths at the operating pressures of 4–5 torr. We attribute this width to the fact that at these pressures the 384.6 \(\mu\)m line is a result of a Raman type coherent scattering resonantly enhanced by the proximity of the \(4_{22}\) level [23], [32]–[33], Fig. 3. This type of process is broadened by pressure broadening, the AC Stark effect and the large linewidth of the selfmodelocked TEA \(\text{CO}_2\) laser. The AC Stark effect broadening occurs because the pump field varies in time and space, while the \(\text{CO}_2\) linewidth broadening occurs because of a spread in the energy of the virtual level in the Raman process. The time resolved picture of the \(\text{CO}_2\) laser pulse taken with a germanium photon drag detector and displayed on a Tektronix 7904 oscilloscope is shown in Fig. 4(a).

To cut down on the ASE background while retaining a long gain path an injection method, based on similar \(\text{CO}_2\) laser systems [34], was tested. The system is shown in Fig. 5. 20 percent of the 200 MW \(\text{CO}_2\) pump beam was directed to the 0.36 m single mode cavity and 80 percent to the 1.55 m cavity which usually oscillated on 3–5 modes. By tuning the length of the two cavities one of the modes of the 1.55 m cavity was made to coincide in frequency with the optimized mode of the 0.36 m cavity. When the output of the single mode cavity was then injected, through a 45° mesh beam splitter, into the 1.55 m cavity the latter was made to oscillate predominantly on the matching mode. Both cavities were oscillating on both 384.6 \(\mu\)m and 359.3 \(\mu\)m lines. The “before and after” injection situation is depicted on Fig. 6. The maximum output from this system was achieved with pressures of 6 Torr of \(\text{D}_2\text{O}\) in both cavities and amounted to about 100 kW peak power on all lines and modes. The injected single mode signal was effective in mode selection even at intensities of a few watts/cm\(^2\).

The injection method was only partially successful in producing a single mode radiation. A more successful method was the use of a short cavity pumped with all of the available \(\text{CO}_2\) power. Only about 30 percent of the \(\text{CO}_2\) pump power was
transmitted through the two meshes of the 0.36 m long cavity, the same as in Fig. 5.

Fig. 7 shows a scanning Fabry-Perot interferogram of the output of the 0.36 m single mode cavity. Fig. 4(b) shows the laser output versus time from the same cavity using a Schottky diode detector and a Tektronix 7904 oscilloscope. A comparison of this pulse with the CO₂ pump pulse, Fig. 4(a), shows that the structure of the pump pulse is not reproduced in the single mode FIR beam. The single mode operation was achieved up to the average pump intensities of 1.7 MW/cm² for a 40 percent reflective output mesh mirror and 1.2 MW/cm² for a 50 percent reflective mesh. Above these pump intensities, the output became multimode at all cavity length settings within the free spectral range. Fig. 8 shows the pressure dependence of the energy of the output of the 0.36 m cavity for various CO₂ average pump intensities and the two different output mesh mirrors. For 1.7 MW/cm² average input pump intensity, which gave the highest power while still retaining a single mode output, we obtained 4.2 mJ FIR energy at the optimum pressure of 10 torr. This energy corresponds to approximately 67 kW peak power on both lines and to over 50 kW peak power on the 384.6 μm line. The energy conversion efficiency, FIR energy out/CO₂ energy in, was about 0.03 percent in this case, or about 0.1 percent if CO₂ beam insertion losses are taken into account. There is an absolute quantum limit on the conversion efficiency, 2.4 percent, corresponding to one FIR photon being emitted for every CO₂ photon absorbed. This limit, theoretically attainable in Raman processes, is further cut down by the off resonant character of the absorption process and gain shape considerations [32]. Maximum efficiency attained in any of the D₂O lasers in this laboratory was about 0.4 percent in an ASE type of laser [35].
Preliminary results indicate that the Fox-Smith mode selector suppresses all but one longitudinal mode. The linewidth of this mode is less than 30 MHz FWHM. When the 45° angle quartz coupler was placed inside the cavity, thus eliminating the CO2 beam losses in transmission through the mesh mirror, 6 mJ, 70 kW output pulses at 384.6 µm were obtained from this system pumped by about 250 MW from our CO2 system operating with an improved gas mixture.

Another promising technique of obtaining high power single mode FIR radiation from a rather long oscillator is to use a Fox-Smith [36] mode selector. A 1.7 m long D2O cavity, shown in Fig. 9, with this type of mode selector has been developed to determine the effectiveness of this approach. Preliminary results indicate that the Fox-Smith mode selector suppresses all but one longitudinal mode. The linewidth of this mode is less than 30 MHz FWHM. When the 45° angle quartz coupler was placed inside the cavity, thus eliminating the CO2 beam losses in transmission through the mesh mirror, 6 mJ, 70 kW output pulses at 384.6 µm were obtained from this system pumped by about 250 MW from our CO2 system operating with an improved gas mixture.

The presence of the 359.3 µm line in the output of most of the D2O lasers should not be treated as a negative factor in the Thomson scattering experiment. The scattered radiation will be detected by heterodyne mixing in a Schottky diode and this line is too far removed in frequency to play any role. Our measurements show that this cascade line, unlike the refilling and cascade lines in CH3F, oscillates at all D2O pressures. We attribute this to the influence of nuclear spin statistics on the degeneracy of the levels [25]. The ratio of the degeneracies of the levels involved is 2:1:2 for the 422,412,404 levels, respectively. This ratio works for the shorter, and against the longer wavelength.

It should be stressed that due to the very high gain of the systems we are dealing with, there is always a possibility of some low level ASE type radiation being present. As indicated previously the ASE radiation is characterized by a very large linewidth. Since for Thomson scattering the ratio of the scattered to the input power is about 10^-14, it is extremely desirable to have a truly ASE free system. According to the analysis of Allen and Peters [37]-[39] it is obvious that the shorter the cavity and the larger its diameter the better the ratio of the power emitted in a single mode to the ASE power in the same angle of divergence as the single mode beam. Thus, short, large diameter oscillator and oscillator-amplifier units appear highly promising for high power laser systems for Thomson scattering measurements.

To get an upper estimate on the possible ASE content in the output of our 0.36 m long single mode cavity, we removed the output mesh mirror in that cavity while externally attenuating the CO2 beam by the same amount as the mesh previously did. The ASE output from this system was about 0.6 mJ. This should be compared with the 4.2 mJ output when the cavity was in operation. Obviously, the competition from the very high intensity single mode radiation should attenuate the ASE radiation very strongly. From our scanning Fabry-Perot interferograms of the output of the cavity we can put an upper limit of 10^-2 on the ratio of the ASE emission to the single mode power. The signal-to-noise ratio made an exact measurement impossible. More sensitive measurements of the ratio of ASE emission to single longitudinal mode power will be made by using heterodyne detection techniques to measure intensity of the output in the wings of the frequency spectrum.

In conclusion, it appears that high power far infrared laser systems can be constructed with the spectral quality necessary for Thomson scattering determination of ion temperature in tokamak plasmas. Great care, however, has to be exercised to prevent ASE contributions to the laser output. The use of very high power oscillators and decreased reliance upon long, high gain amplifier sections seems to be required. Fox-Smith mode selection techniques may provide a means of obtaining single longitudinal mode operation in a relatively long laser oscillator.

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