A High-Power Far-Infrared NH₃ Laser Pumped in a Three-Mirror CO₂ Laser Cavity with Optically-Switched Cavity-Dumping

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Results are reported of cavity-dumping a submillimeter radiation high-Q, zig-zag optically-pumped resonator which utilizes a silicon optical switch photo-excited by a Nd:YAG laser. Peak powers at 152 μm approaching 10 kW in temporally smooth pulses of 5 ns (FWHM) duration have been obtained at a pulse repetition rate of 12 Hz. The far-infrared laser radiation, as measured with a scanning metal-mesh Fabry-Perot interferometer and averaged over many pulses, is, upon deconvolution of the 125 MHz instrumental linewidth, found to oscillate in a predominantly single longitudinal mode of width 250 MHz. Theoretical investigations of the transient far-infrared reflectivity of the silicon optical switch predict a rise in the Brewster-angle reflectivity from 0% to nearly 80% in 1 ns, when activated by a Q-switched, frequency-doubled Nd:YAG laser providing an incident energy density of 50 mJ/cm² in a pulsewidth of 10 ns.

Key words: optical-switching, cavity-dumping, far-infrared laser.

Since the author first reported on a novel technique for laser cavity-dumping in the far-infrared spectral range¹, a number of investigators also have demonstrated its use² and promise for time-resolved far-infrared spectroscopy. Here we report some new characterization studies of the cavity-dumped radiation and theoretical investigations concerning the plasma dynamics and
associated transient reflectivity of the photo-excited silicon optical switch.

The optically-pumped far-infrared $\text{NH}_3$ laser, with the exception of the cavity-dumping module, as described previously, is a slight modification to an earlier design by Hirose et al. A schematic diagram of the far-infrared resonator is shown below in figure 1. Recent improvements have been made by changing mirror M1 to a concave mirror with a radius of curvature 32 m. and similarly, by changing the radius of curvature of mirror M4 to 97 m. The resulting smaller beam waist ($\pi w_0 = 0.54 \text{ cm at } \lambda = 152 \mu\text{m}$) is located at the midpoint of the silicon wafer, 1.0 m from M4. The beam diameter at mirror M4 is 8.6 cm. After passing through a cylindrical lens, the output of a GCR-11 Nd:YAG laser is introduced through window W2 and irradiates that portion of the surface of the silicon wafer exposed to the beam waist of the far-infrared radiation. The YAG laser profile on the silicon wafer is approximately elliptical in shape with major and minor axes of lengths 35 and 7 mm, respectively. This is to be compared with the projection of the far-infrared beam waist onto the silicon wafer, an ellipse with major and minor axes of 19 and 5.4 mm., respectively, for a TEM$_{00}$ intracavity mode.

![Schematic diagram of the far-infrared resonator.](image)

Figure 1: Schematic diagram of the far-infrared resonator.

$\text{NH}_3$ Laser

Not shown in Figure 1 is a Gentec\textsuperscript{5} laser, which provides 375 mJ/pulse (0.1 mm). The laser employs a 150 groove/mm grating coupler of reflectivity 80\% and 10 mrad acceptance angle. The output consists of a gain-switched spike with duration containing a high-degree of multiphoton oscillations.

Optical switching of far-infrared (FIR) laser-induced excitation of a dense electron gas in a semiconductor was first demonstrated by the authors described previously, we have achieved a near-complete cavity-dumping a high-Q, FIR molecular gas. A high-purity ($\rho = 6000 \Omega\cdot\text{cm}$) silicon wafer, 100 mm diameter, is held in an adjustable mount near the Brewster angle ($\Theta_B = 74^\circ$). Near the Brewster angle, with the absence of optical switching. The wafer is illuminated by a short-pulsed, frequency-doubled $\text{CO}_2$ laser. Within 1 ns, the silicon wafer is turned on, which dumps the resonator's stored energy into the FIR radiation corresponding to the optical transitions of the resonator, about 5 ns. Figure 2a below shows a typical intensity trace, as captured with a 1 MHz bandwidth) pyroelectric detector\textsuperscript{5} and a laconic $\text{CO}_2$ laser. The peak power is 10 MW.
Not shown in Figure 1 is a Gentec® DD-250 TEA CO₂ pump laser, which provides 375 mJ/pulse (multi-mode) on the 10P32 line. The laser employs a 150 groove/mm grating with a Ge output coupler of reflectivity 80% and 10 m radius of curvature. The CO₂ output consists of a gain-switched spike of approximately 200 ns duration containing a high-degree of mode-beating.

Optical switching of far-infrared (FIR) radiation by the laser-induced excitation of a dense electron plasma in a high-purity semiconductor was first demonstrated by Salzmann et al.⁶ As described previously, we have achieved a novel means of cavity-dumping a high-Q, FIR molecular gas laser in the following manner. A high-purity (ρ=6000 Ω-cm) silicon wafer⁷, 10 cm in diameter, is held in an adjustable mount inside the FIR resonator near the Brewster angle (θB=74°) with low reflectance and loss in the absence of optical switching. The FIR laser energy is allowed to build up to its maximum value and then the silicon is illuminated by a short-pulsed, frequency-doubled Q-switched Nd:YAG laser. Within 1 ns, the silicon wafer is turned into a highly reflective mirror which dumps the resonator's stored energy in an intense pulse of FIR radiation corresponding to the optical transit time in the resonator, about 5 ns. Figure 2a below shows a typical cavity-dumped pulse, as captured with a Molelectron P5-00 fast (700 MHz bandwidth) pyroelectric detector⁸, and a Tektronix 2467B/DCS01 oscilloscope/digitizing camera system⁹ with an effective bandwidth of 400 MHz.

![Graph](image1)

**Figure 2**: Cavity-dumped intensity versus time for the 152μm line of NH₃ as obtained with a (a) pyroelectric detector (b) Schottky-barrier diode detector. The peak power is 10 kW.
The peak power is found to be 10 kW from independent measurements taken with both a P5-00 pyroelectric detector and a Scientech 362 thermopile detector. Figure 2b displays the pulse profile obtained with a faster room-temperature corner-cube Schottky-barrier diode detector and a Tektronix SC5000 transient waveform recorder (4.5 GHz bandwidth). However, approximately, 25% of the pulses have a more irregular shape.

In order to determine the average linewidth, a scanning metal-mesh Fabry-Perot interferometer (SFPI) with a finesse of 50, was used in high order. The SFPI was constructed by the author and will be described in detail elsewhere. It uses two Buckbee-Mears MN-1000 optical filters stretched taut over two Newport Corporation optical flats, with 50 mm holes, held in gimbals on precision translation stages. The finesse, as determined from a first order interferogram, is in agreement with theory. One of the translation stages is driven by a piezoelectric actuator, a Burleigh PZ-030-6, under computer control. The piezoelectric actuator was calibrated by taking an interferogram of the output of a helium-neon laser with the SFPI. Figure 3a shows a high-order scan (resolving power $1.6 \times 10^4$) of the FIR radiation using the P5-00 in conjunction with a Stanford Research Systems SR250 boxcar averaging system. Each data point shown in figure 3a is the average intensity of 360 pulses. The cavity-dumped radiation is seen in fig. 3b, upon deconvolution, to consist predominantly of a single longitudinal mode of bandwidth 250 MHz.

![Diagram](image)

Figure 3: Linewidth measurements using a scanning Fabry-Perot (FP) interferometer: (a) Boxcar averaged scan data (b) Deconvolution of the instrumental response: Inner curve is FP response, outer curve is fit to data shown in (a), middle curve is the deconvolved linewidth.

![Diagram](image)

Figure 4: Cavity-dumped FIR intensity gain-switched peak of the CO$_2$ laser.

In order to determine the optimum far-infrared resonator's energy, a time boxcar averager, was taken of the duration of the YAG laser Q-switch delay as measured CO$_2$ laser output. Figure 4 shows that the output occurs at a surprisingly large delay of poor pulse-to-pulse reproducibility in the thought to be the result of the unstable multi-mode TEA CO$_2$ pump laser power upgrade the multi-mode TEA CO$_2$ laser TEA laser cavity employing a low-power stable single-longitudinal mode output.

Because of its relevance to our experiment, modeled the time-dependent far-infrared silicon optical-switch. A number of investigators detail the transient infrared (usually 1) semiconductors under laser-induced conditions considered here. The absorption in semiconductors leads to the creation of electron-hole pairs and elevated carrier density according to the classical Drude model of the optical properties through the free-electron density and dielectric constant $\varepsilon(\omega)$. The Drude model has been shown to successfully describe the properties of extrinsically doped semiconductors with frequencies below the associated...
Figure 4: Cavity-dumped FIR intensity versus delay time from the gain-switched peak of the CO$_2$ laser. The NH$_3$ pressure is 3 Torr.

In order to determine the optimum time at which to dump the far-infrared resonator’s energy, a time scan, using the SR250 boxcar averager, was taken of the dumped intensity versus the YAG laser Q-switch delay as measured from the initiation of the CO$_2$ laser output. Figure 4 shows that the maximum intensity occurs at a surprisingly large delay of approximately 1.5-2 $\mu$s. The poor pulse-to-pulse reproducibility in the FIR output power is thought to be the result of the unstable temporal modulation of the multi-mode TEA CO$_2$ pump laser power. Work is in progress to upgrade the multi-mode TEA CO$_2$ laser to an Invar-stabilized hybrid TEA laser$^{17}$ cavity employing a low-pressure gain cell to produce stable single-longitudinal mode output.

Because of its relevance to our experiments, the author has modeled the time-dependent far-infrared transient reflectivity of the silicon optical-switch. A number of investigators$^{18}$ have studied in detail the transient infrared (usually 10.6 $\mu$m) reflectivity of semiconductors under laser-induced excitation conditions similar to those considered here. The absorption of pulsed laser radiation by semiconductors leads to the creation of nonequilibrium carrier densities and elevated carrier and lattice temperatures which, according to the classical Drude model for free carriers, determines the optical properties through the frequency-dependent complex dielectric constant $\varepsilon(\omega)$. The Drude model for free carriers has been shown to successfully describe the far-infrared optical properties of extrinsically doped semiconductors$^{19}$. All radiation with frequencies below the associated plasma frequency is totally
Figure 5: (a) reflectivity for 152 μm radiation incident upon a silicon surface exposed to 50 mJ/cm² of 10 ns 532 nm radiation (b) carrier density at the surface versus time.

Reflected from the surface, provided the skin depth of the radiation is less than the characteristic plasma depth. The temporal and spatial evolution of the carrier density and carrier-lattice temperature are governed by coupled nonlinear diffusion equations, subject to the appropriate boundary conditions. These diffusion equations have been solved simultaneously for the carrier density and lattice-carrier temperature using standard finite difference techniques and the Crank-Nicholson method for the particular case of silicon irradiated by a 10 ns (FWHM) Gaussian pulse of 532 nm radiation containing 50 mJ/cm² of energy density. The carriers generated by pulsed laser absorption are spatially inhomogeneous due to absorption, diffusion, and Auger lifetime effects. We have determined the far-infrared reflectivity for a transverse magnetic (TM) wave incident at the Brewster angle on the optically absorbing inhomogeneous silicon optical switch by using the characteristic matrix method for stratified media. We will report on the details of these calculations at a later date. Figure 5a shows the reflectivity for a 152 μm TM wave as a function of time. The origin of time is taken to be 10 ns before the peak of the 532 nm pulse. The reflectivity is seen to reach 80% within 1 ns. Figure 5b shows the calculated surface carrier density versus time under identical conditions of illumination; the carrier density is seen to surpass 10¹⁸ cm⁻³ within 1 ns.

Such a source of high-power, temporally-smooth FIR pulses may be of interest in new experiments in time-resolved FIR spectroscopy. One such experiment would investigate the generation of coherent pulses of monochromatic acoustic phonons in the terahertz frequency regime by resonant phonon excitation by the FIR laser pulses in modulation δ-doped silicon superlattices.

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Notes: (1) Most of this paper was originally presented at the International Conference on Lasers ‘91, subsequently published in the SOQUEL conference proceedings, p. 762, Eds: F.J. Duarte and D.G. Harrington, (Pittsburgh, VA) 1992. (2) Stable cavity-dumped pulsed lasers have been obtained at 496 microns in CH₂F₂ and 9P20 CO₂ laser lines.

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Analysis and Design of NRD-Guide E-Plane Y-Junction Circulator

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ABSTRACT

A new type of E-plane Y-junction circulator has been developed based on the nonradiative waveguide (NRD-guide) in Ka-band. First, the structure has been analyzed by the theory of electromagnetic field components in the nonreciprocal media. The conclusion shows that the implementation of 60° phase difference and counterclockwise rotating polarization of the output wave can be obtained. And then, the resonant frequency and the resonant frequency of the Y-junction circulator are measured. A strongly biased triangle ferrite sample is chosen for the fabricated Y-junction circulator. A Y-junction circulator is fabricated using the NRD-guide. The measurement frequency is 35.1GHz, the isolation bandwidth is about 1.0GHz.

I. INTRODUCTION

Circulator is a kind of important device in millimeter wave circuits. Because of the easily adjustable and good performance, it is widely used as a duplexer and is an essential component of the millimeter wave circuits. This paper introduces the design and realization of a novel type of Y-junction circulator based on the nonradiative waveguide (NRD-guide) in Ka-band. Theoretical analysis and experimental results are presented.

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