Proc. SPIE 4635, 57-64 (2002) Photonics West (SPIE) Jan 2002

Far-IR semiconductor laser for future THz-carrier free-space communications

R. E. Peale*[a], A. V. Muravjov[a], E. W. Nelson[a], C. J. Fredricksen**[b], S. G. Pavlov[c], V. N. Shastin[c]
[a]Department of Physics, University of Central Florida; [b]Zaubertek, Inc.;
[c]Institute for Physics of Microstructures, Russian Academy of Sciences

ABSTRACT

New experimental results are presented for the far-infrared p-Ge laser that enhance its prospects for application to secure satellite and short-range terrestrial free-space communications on a THz carrier. An optical means of gain modulation has been discovered that may potentially permit far-IR pulse generation via active mode-locking with low drive power. A compact high-field permanent-magnet assembly is demonstrated for applying the magnetic field required for laser operation without need of liquid helium. Compact light-weight laser-excitation electronics have been designed to run off a low voltage direct current supply.

Keywords: terahertz, submillimeter wavelength, far-infrared, laser, laser communication, satellite communication

1. INTRODUCTION

Free space communications using THz carrier frequencies is severely constrained by atmospheric water vapor absorption. Areas of application are limited to secure short-range communications and high altitude or extra-terrestrial communications.[1] To appreciate the terrestrial limits of a THz carrier, note that the minimum attenuation per unit length and per unit absolute humidity in the 1.5 –3 THz region is about 20 dB-m^3/km-g.[1] At conditions of 25 C and 60 % relative humidity, the absolute humidity is about[2] 14 g/m^3 giving a minimum attenuation of 280 dB/km. Hence, at least half the propagating THz power will be lost after just 11 m path length. For some THz wavelengths, maximum attenuation exceeds 1000 dB-m^3/km-g, giving a -3 dB range below 20 cm for the example conditions.[1]

The measured attenuation depends on the spectral resolution if the water bands are not resolved, as was the case in Reference 1. If water bands are better resolved, narrow windows of higher transmission will be found, but with potentially unacceptable restrictions on bandwidth. Similarly, peak losses will increase for certain wavelengths.

The water-free high altitude and extra-terrestrial domains are closer to the area of interest of the Air Force, which partially supports this work (see acknowledgments). Airborne/satellite communications were specifically mentioned in the original proposal call for new THz sources. Satellite-to-satellite laser communications is generally very attractive. Global coverage can be achieved with as few as three synchronous satellites.[3] Intersatellite communications in single line-of-sight hops can have very high data rates, can eliminate unreliable ground links and interconnects, and can have high security and reliability during times of war or political unrest.

THz carrier frequencies have been considered for inter-satellite communications for at least 3 decades.[3] An advantage of sub-millimeter-wave carriers (over millimeter-wave) for satellite applications is that narrow beams, which have obvious privacy and efficiency benefits, can be achieved with smaller apertures. Secondly, as usual, data bandwidth increases with frequency. Additionally, the strong absorption of the atmosphere blanketing the earth provides a very high level of security.

Some advantages of lasers for satellite communications over solid-state power devices are greater potential data rate, smaller size and weight, and lower power consumption.[3] Recent examples of laser satellite communications experiments

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*rep@physics.ucf.edu; **info@zaubertek.com, www.zaubertek.com.

include the National Reconnaissance Office's GeoLite satellite launched recently[4] and the Artemis satellite[5] of the European Space Agency, launched on 12 July 2001 and unfortunately stranded in a useless orbit.[6] However, no suitable *THz* emitter, laser or otherwise, currently exists for communications. This paper discusses some recent developments for a specific THz laser source, the far-IR p-Ge laser, which may make it suitable for future satellite communications on a THz carrier.

The p-Ge laser operates in the 1.5 to 4.2 THz region with watt-level output power.[7] The laser mechanism is based on inversion population between light- and heavy-hole valence sub-bands in crossed electric and magnetic fields. Picosecond pulses of far-IR radiation can be generated[8,9] by actively mode-locking, where the gain is modulated using rf power applied to additional ohmic contacts. The pulse train of a harmonically mode locked p-Ge laser can be electrically modulated.[10] However, active mode-locking so far has required large rf power, which is incompatible with satellite requirements.

2. OPTICAL MODULATION OF FAR-INFRARED GAIN

We report here a demonstration of a non-contact optical-modulation scheme, which potentially might be used for short pulse generation via active mode-locking. This is made possible by use of a $SrTiO_3$ laser mirror, which is highly reflecting in the p-Ge laser emission range and highly transparent for wavelengths shorter than 7 μm.

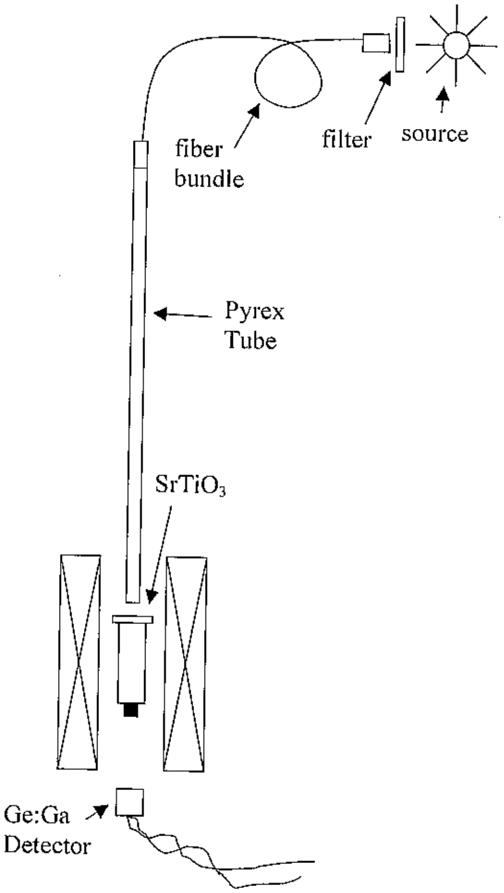

Fig. 1 Schematic of experimental set-up for optical modulation of far-infrared laser gain. Light from a variety of laser or filtered-broadband sources is conducted to the $SrTiO_3$ laser mirror via a fiber bundle and glass tube. Laser signal is detected with a Ge:Ga photoconductor, which is immersed in liquid helium at 4 K, together with the superconducting magnet and active crystal.

Fig. 1 shows the experimental set-up. For these experiments a monocrystalline p-type germanium rectangular rod was prepared with polished parallel end faces (within 30 arcseconds) and ohmic contacts on a pair of opposite lateral surfaces. The concentration of gallium acceptors was 7 x 10^{13} cm^{-3}. The crystal dimensions were 50 mm x 7 mm x 5 mm. One laser mirror was cut from standard $SrTiO_3$ substrate polished on both sides. The other mirror was copper, insulated from the crystal by 20 μm teflon film. The 5 mm diameter of the copper mirror was smaller than the aperture of the active crystal to allow output coupling of the laser radiation, which was detected by a Ge:Ga photoconductor. The system was placed into a superconducting magnet and immersed in a storage dewar that contained liquid helium at 4 K. Magnetic fields from 0.5 to 1.5 T were applied. A thyratron pulser applied ~1 kV/cm x 1 μs x 1 Hz electric pulses to excite the active crystal. For optical modulation of the gain, a fiber bundle and glass tube conducted light from a variety of sources to the end face of the laser crystal through the $SrTiO_3$ mirror. Sources included a xenon arc lamp with high and low pass filters, pulses from a fundamental- or doubled-Nd:YAG laser in Q-switched or long-pulse mode, and a near infrared laser diode, as shown in Fig. 2. The timing of the YAG relative to the p-Ge laser excitation and far-IR emission pulses was monitored with a fast Si avalanche diode.

Modulation of the laser gain was observed as a quenching of the laser emission. The effect was strongest for wavelengths nearest the germanium band gap (Figs. 2 and 3). The Q-switched YAG laser with 8 ns pulse duration allowed us to determine that the effect was strongest when the radiation was incident on the crystal at the beginning of the p-Ge laser electrical excitation, when the population inversion is building up.

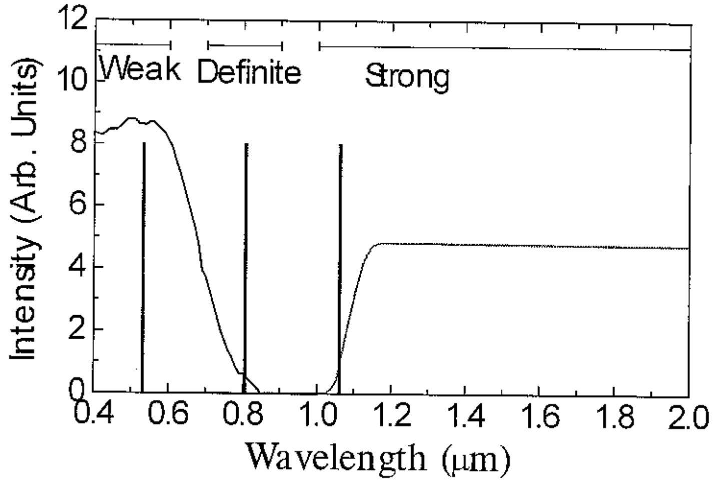

Fig. 2. Schematic of wavelength content of the near-IR and visible sources used. The two curves correspond to Xe-arc lamp emission transmitted either by an IR absorbing filter (Schott KG5) or by a long-pass silicon filter. The three vertical bars represent the laser wavelengths used (Nd:YAG at 532 or 1064 nm, or a laser diode at 806 nm.) The strength of the laser-quenching effect for different optical wavelengths is qualitatively indicated. The vertical scale is meaningless since it was impossible to compare the relative power incident on the laser for each source in this first experiment.

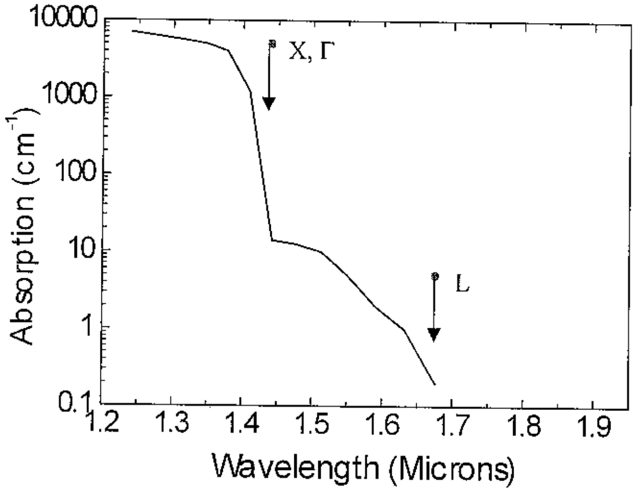

Fig. 3. Absorption coefficient vs. wavelength for Ge at 4K showing positions of conduction band minima.

Quenching of far-infrared laser emission by optical perturbation also depended on where in its generation zone the p-Ge laser operated (Fig. 4). The most remarkable effect was observed on the upper border where the laser threshold is sharp. The effect is weaker on the lower border, where the lasing threshold is less sharp. In the center of the laser zone, where the p-Ge laser gain is highest, the laser emission was not quenched by the optical irradiation. These results are in agreement with the earlier electrical modulation results, where (especially in Faraday configuration of applied fields[9]) mode-locking was easiest to obtain near the border of the generation zone.

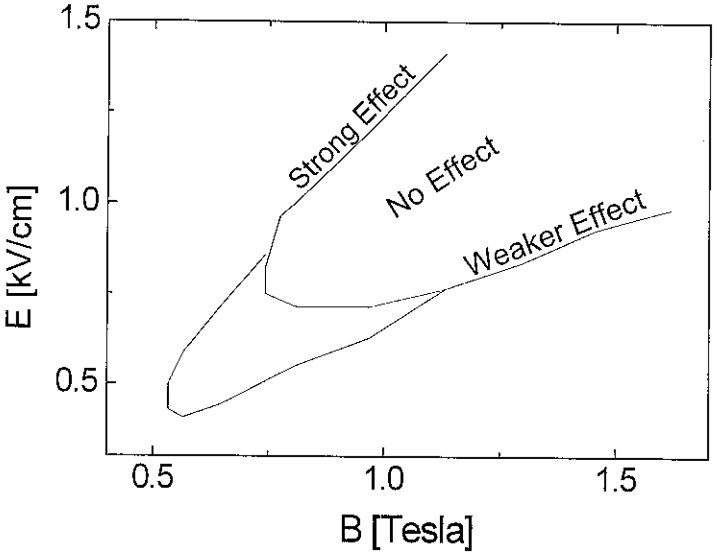

Fig. 4. Generation zone for p-Ge laser with qualitative indication of quenching by optical irradiation on one end face of the active crystal.

Fig. 5 shows a proposed mode-locking scheme where laser gain might be optically modulated at the cavity round-trip time. This would have several potential advantages over the previous electrical modulation methods.[8-10] There would be no need for additional ohmic contacts, whose placement is critical and difficult to change. The old electrical modulation scheme[8-10] required ~100 W of applied rf, but optical modulation using laser diodes might be much more efficient and less of a heat load. The high modulation speeds possible with telecom laser diodes might make it much more convenient to optimize the modulation of the far-IR laser gain. For the same reason, harmonic mode-locking with pulse-position modulation[10] might be possible using sophisticated telecom hardware. Because the absorption depth for above-gap radiation in germanium is only about 1 micron (Fig. 3), optical modulation might give much shorter far-IR pulse duration than electrical modulation, which perturbs the active crystal over mm length scales.[8-10]

As a caution, we note that use of fundamental band-gap absorption to modulate the inter-valence band gain might be limited by the life time of the generated electron-hole pairs, which should be large compared with the ~ns photon round-trip times in typical p-Ge laser cavities. Hence, the mechanism of the fast gain modulation required for mode-locking is unlikely to be based on changes in hole and electron concentrations. Still, optical pumping will likely change the hole distribution function, and under conditions for inversion population the gain will be affected. In that case, the reaction will be at least as fast as the longest hole lifetime, e.g. 10^{-10} sec, which might suffice for modelocking.

We note also that there appear to be several different mechanisms of far-IR gain modulation by optical irradiation, since effects were observed with a wide range of time scales. The slowest effects were compatible with a thermal explanation. The fastest observed effects, using the Q-switched YAG laser pulses with variable delay, were on the ~100 ns scale of the p-Ge laser build-up time, which is compatible with electron-hole pair generation and lifetime. Fast changes in hole distribution function, which would be needed for mode-locking, could not be directly observed with the existing set up, nor has the potential efficiency been estimated. Fast time resolved measurements are needed to study this phenomenon. Use of femtosecond near-infrared laser pumping with fast Far-IR detection of the p-Ge laser emission using a Schottky detector and transient digitizer[8-10] are suggested.

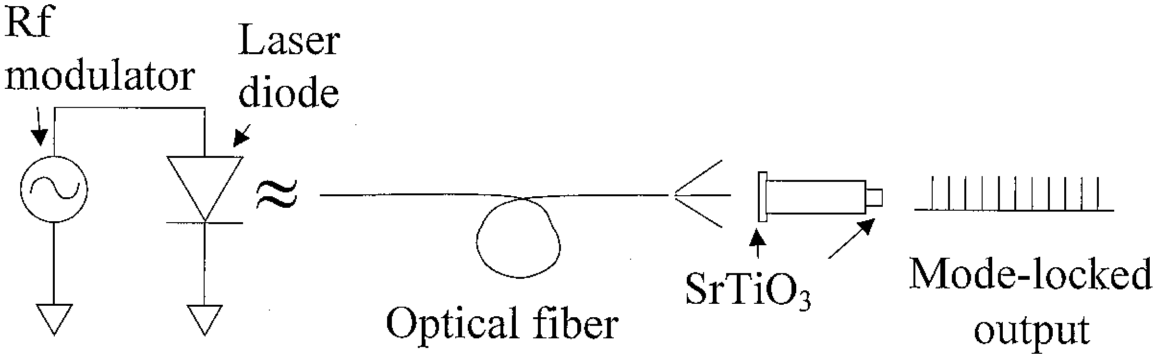

Fig. 5. Proposal for far-IR short-pulse generation from p-Ge lasers by optical gain modulation at one end surface of the active laser crystal.

3. PERMANENT MAGNETS

Liquid-helium cooled superconducting magnets, as shown in Fig. 1, are inconvenient for terrestrial applications, and practically prohibited for airborne/satellite applications. Hence, a permanent magnet assembly that can provide the necessary uniform magnetic fields without cooling was tested. Fig. 6 shows a SmCo and stainless steel magnet assembly (Magnet Sales) with calculated field lines (FlexPDE). The field measured between the poles with a Hall probe was 0.7 T at room temperature. The p-Ge active crystal is placed within the rectangular gap at center, where the field is evidently quite uniform over a large volume.

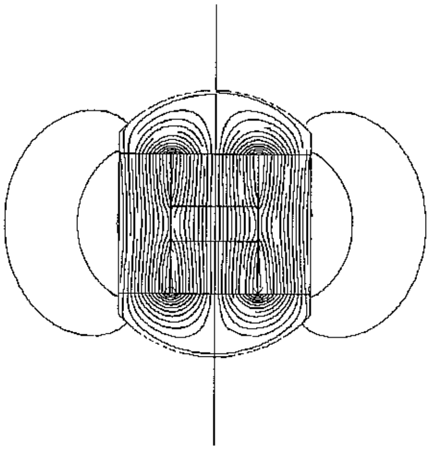

Fig. 6. SmCo and stainless steel magnet assembly (Magnet Sales, Inc.) with calculated field lines.

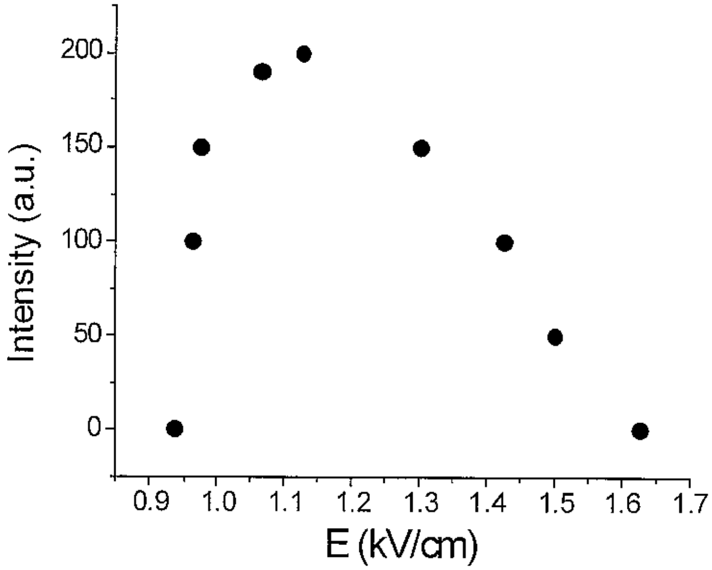

Fig. 7 Laser emission intensity vs applied electric field for a p-Ge laser in the Fig. 6 permanent magnet assembly.

4. ELECTRONICS

Usual excitation electronics for p-Ge lasers are patchworks of bulky, heavy, expensive instruments, shown schematically in Fig. 8. We have designed an integrated system with improved performance, robustness, and cost effectiveness (Fig. 8). The entire package has dimensions 15 cm x 15 cm x 40 cm and weighs approximately 2 kg. Particular attention has been paid to shielding, reduction of electro-magnetic interference for low noise applications, and lowering of power requirements. The system is powered by 12 V DC.

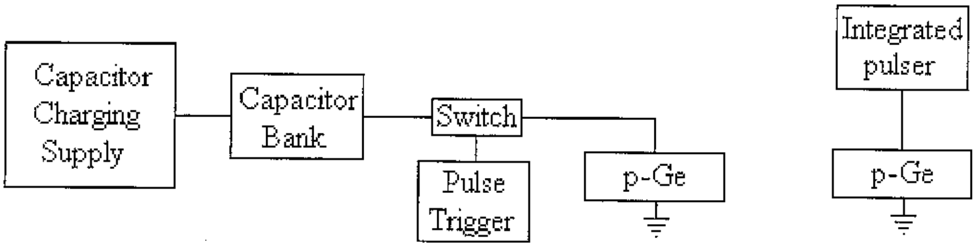

Fig. 8. Block schematic of old (left) and new (right) p-Ge laser excitation electronics.

The solid state switch is composed of a parallel and series combination of fast MOSFETs. The target rise and fall time for switching several hundred volt pulses with ~ hundred ampere currents is 10 ns. Clamping circuits are implemented to quench the flyback voltages and oscillations, which arise from the extremely fast switching of large currents. The printed circuit board and enclosure are designed to isolate the interference generated by the switched high currents.

Pulse shape is degraded by mismatched transmission from pulser to low-impedance active crystal. Pulse transformers with 10:1 turn ratio and 100 kHz-100 MHz bandwidth will be implemented at both pulser output and load to allow use of ordinary 50 ohm cable, as indicated schematically in Fig. 9.

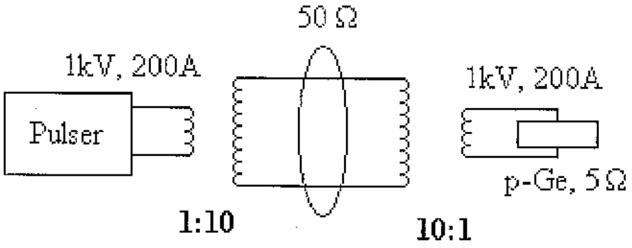

Fig. 9. Impedance matching transformers to allow use of ordinary coax between pulser and load without degrading pulse shape.

5. SUMMARY

Secure short-range terrestrial and long-range extra-terrestrial communications are attractive potential applications for a laser operating in the THz region of the electromagnetic spectrum. The far-infrared p-Ge laser is the only solid state laser in this region. It has many attractive features for communications, including a very wide bandwidth, high output power, and the possibility of generating and modulating short pulses. A number of developments, which are steps toward use of the p-Ge laser in a future communications system, were reported here. These include the discovery of non-contact optical gain modulation, demonstration of a high-field permanent magnet assembly, and the design of compact light-weight laser-excitation electronics.

ACNOWLEDGMENTS

This work was supported by an STTR Phase I award from Air Force Office of Scientific Research (F49620-01-C-0012) and by the National Science Foundation (ECS-0070228).

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