Two color far infrared laser interferometer

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Two color interferometer using a short wavelength far infrared laser has been developed for high performance plasmas on large helical device and for future fusion devices such as ITER. High power laser lines simultaneously oscillating at 57.2 and 47.6 μm were achieved in a CO_2-laser-pumped CH_3OD laser. By introducing Ge:Ga photoconductive detectors operating at liquid He temperature, we have successfully detected two color beat signals (0.55 and 1.2 MHz) with excellent signal-to-noise ratio (~40 dB). These beat signals were fed into phase comparators for phase measurement after passing through intermediate frequency bandpass filters. Two color far infraned laser interferometer work was successful in the demonstration of mechanical vibration compensation. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2219992]

I. INTRODUCTION

For high density operation of the large helical device[1] (LHD) and for future large fusion devices such as ITER, we have been developing short wavelength far infrared laser oscillation lines[2,3] by using CO_2-laser-pumped far infrared (FIR) laser. On the LHD, a 13-channel 119 μm CH_3OH laser interferometer[4] has routinely been operated to provide the electron density profile almost every shot except in the case of an ice pellet injection. On the recent LHD experiments, we have successfully achieved high performance plasmas with very high central electron density of around 4×10^{20} m^{-3} by recycling control by means of the local island divertor[5] combined with pellet injection. In these high density plasmas, fringe jumps on the density traces measured by the FIR laser interferometer sometimes occur at the time of pellet injection. So we have been developing laser sources in the wavelength region around 50 μm to overcome this difficulty and achieved high power laser lines oscillating simultaneously at 57.2 μm (~1.6 W) and 47.6 μm (~0.8 W) in a twin optically pumped far infrared CH_3OD laser. These two color laser oscillation lines enable us to construct a two color laser interferometer.[6] This two color interferometer system is a unique one compared with the conventional two color interferometer system, where two independent lasers are used to be combined: 3.39 μm He–Ne/0.63 μm He–Ne lasers,[7] 10.6 μm CO_2/0.63 μm He–Ne lasers,[8] 10.6 μm CO_2/1.06 μm yttrium aluminum garnet (YAG) lasers,[9] 10.6 μm CO_2/9.27 μm CO_2 lasers,[10] 119 μm CH_3OH/0.63 μm He–Ne lasers,[11] and 195 μm DCN/119 μm CH_3OH lasers.[12] By introducing Ge:Ga detectors operating at liquid He temperature, we have successfully detected two color beat signals with excellent signal-to-noise ratio (~40 dB). In this article simulation experimental results using a test stand will be presented.

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II. TWO COLOR FIR LASER INTERFEROMETER

Figure 1 shows the conceptual design of the interferometer using a two color far infrared laser system. A Martin-Puplett diplexer is placed in front of the laser output, since 57.2 and 46.7 μm laser lines have different polarization. One of the key issues to realize this diagnostic instrument is the development of high quality detectors with fast and sensitive heterodyne detection. There are three candidates used in the FIR wavelength regime, a GaAs Schottky barrier diode mixer, an InSb He-cooled detector, and a gallium-doped germanium detector. The GaAs Schottky barrier diode mixer has widely been used in many FIR laser diagnostics since the detector can be operated at room temperature with high sensitivity. The sensitivity of the detector, however, is decreased with operating frequency due to the cutoff frequency below several terahertz, and it is difficult to make tuning of the detector simultaneously with both frequencies. The InSb He-cooled detector with magnetic tuning has been applied[12] on JET tokamak to simultaneously detect a 195 μm DCN laser and a 118.8 μm CH_3OH laser. The spectral responsivity of the detector, which is normally limited in the frequency region of 60–600 GHz, can be tuned to a specified frequency up to about 3 THz by means of magnetic field, but not over than 3 THz. Then we finally chose a gallium-doped germanium detector operating at liquid He temperature.

Figure 2 shows a view of the detector/cone assemblies mounted on the cold plate of the cryostat. The cooled detec-

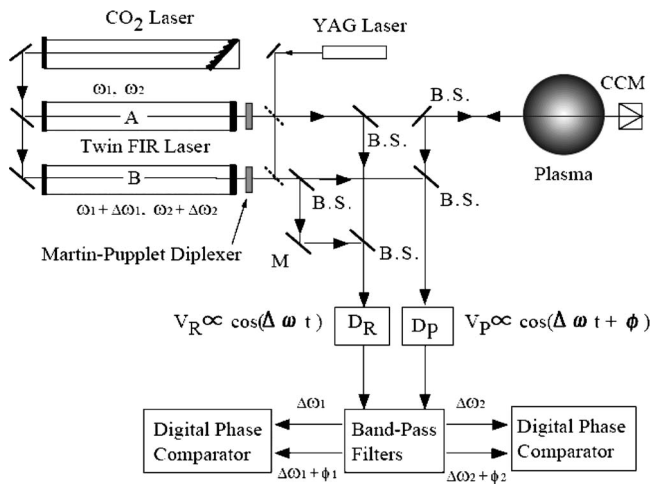

FIG. 1. Conceptual design of the interferometer using a two color far infrared laser system.

tor system contains three unstressed gallium-doped germanium photoconductors. The detectors view incoming radiation via a focusing Winston cone and through a set of low-pass filters via vacuum windows located on the bottom plate of the cryostat. The detecting elements are small compared to the beam size so they are mounted in integrating cavities immediately behind a Winston cone which has an entrance aperture of 15 mm in diameter and has an $f/3.5$ field of view. This arrangement permits multipass absorption by the detector, thereby significantly improving optical coupling efficiency. Two filters are located in the detector system. The first one is mounted on the 77 K radiation shield, where it serves to block and reflect unwanted higher frequencies from the 300 K background radiation. This greatly reduces the thermal load on the cryogenic stages of the cryostat and generates a conveniently long run time from a single fill of liquid helium. The second identical filter sits on the entrance aperture of the Winston cone where it ensures that no unwanted higher frequencies are incident on the detector from leakage within the cryostat. These copper colored structures can be seen in Fig. 2. The transmission spectrum of this filter

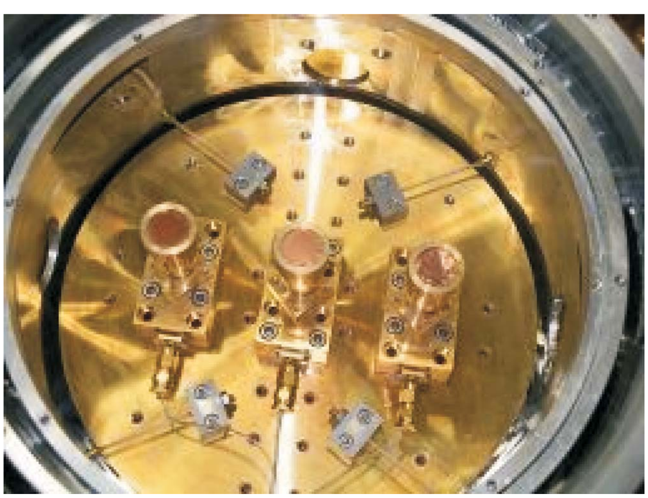

FIG. 2. (Color online) A bottom looking photograph of the cooled detector system which contains three unstressed gallium-doped germanium photoconductors with a focusing Winston cone.

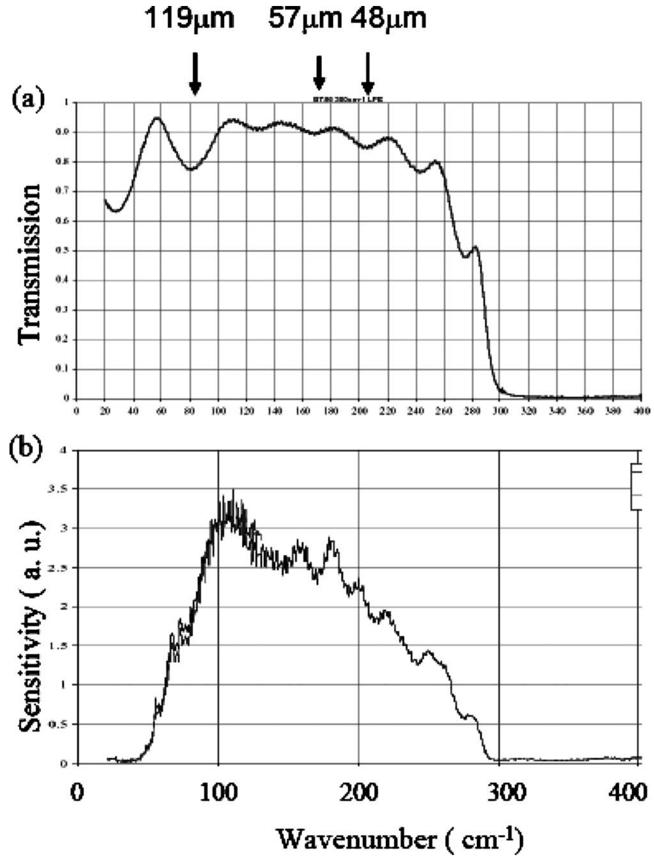

FIG. 3. (a) The transmission spectrum of the low-pass filter showing high transmission efficiency at both laser frequencies (85%–90%). (b) The overall response function of the detector system including the filters and vacuum window.

is shown in Fig. 3(a). Transmission efficiency at both laser frequencies is high (85%–90%) while a sharp cutoff ensures maximum blockage of thermal radiation above the frequencies of interest. The detector is doped with gallium by neutron transmutation. This material exhibits an efficient response to frequencies above 2.4 THz, with peak sensitivity at 3 THz. Toward higher frequencies these detectors exhibit a response which falls in inverse proportion to the frequency. The spectral response of this system is therefore limited to high frequencies by the transmission of the filters. The overall response function of the system (including the filters and vacuum window) is shown in Fig. 3(b). The system is optimized for our two laser frequencies to within a factor of 2. Alternative filters can be used in the system to extend the response of the system to higher frequencies. Low-pass filters of this type are available with cutoff frequencies up to 15 THz.

III. SIMULATION EXPERIMENTAL RESULTS

Figure 4 shows the experimental setup to demonstrate the idea of the two color interferometer. The main components of the interferometer installed on the optical bench are a twin FIR laser, beam splitters, and Ge:Ga detectors. The beam splitters are made of nondoped silicon with high resistivity (~2.8 $k\Omega$ cm). In the FIR regime, crystal quartz etalon has widely been used as beam splitters and windows since

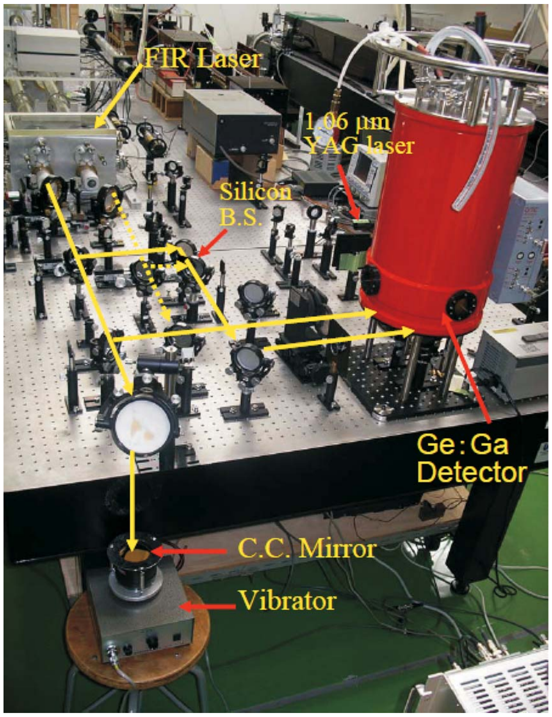

FIG. 4. (Color online) Photograph of the test stand under development for the application of the two color laser.

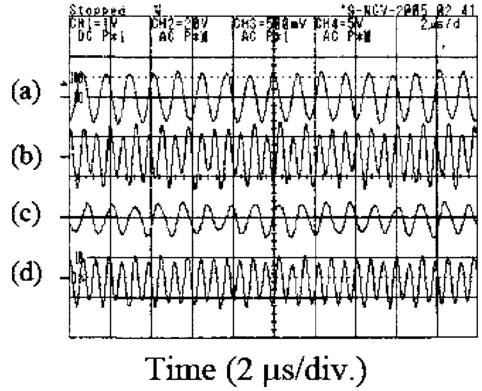

FIG. 6. Sinusoidal waves of two color beat signals after passing through bandpass filters. (a) and (b) are the beat signals of 57.2 and 47.6 μm for a reference chord. (c) and (d) are the beat signals of 57.2 and 47.6 μm for a probe chord.

crystal quartz is a low absorption material (0.46 cm^{-1} at 118.8 μm) in long wavelength FIR regime and transparent to visible light. However, the measured absorption coefficient of quartz at 47.6 μm is about ten times larger than that at 118.8 μm. So we have measured optical constants[13] of several optical materials suitable for the short wavelength FIR regime and found that a silicon etalon with high resistivity is a useful material in this regime. In the figure, an YAG laser (wavelength: 1.06 μm, power: 100 mW) is used for the alignment of the interferometer since the visible He–Ne laser is not transmitted through silicon. Figure 5 shows the frequency spectrum of two color beat signals at 1.2 MHz for 57.2 μm and 0.55 MHz for 47.6 μm. It can be seen in this figure that the signal-to-noise ratio is excellent to be about 40 dB. This high signal-to-noise ratio was achieved when the input power to the detector was reduced by 30 dB. The beat frequency of each laser oscillation line can be set at the optimum value by changing the pressure of the FIR laser cavity and by tuning the cavity length. The optimum value of the beat frequency is determined from the following factors: detector band width (3 dB bandwidth is 2 kHz–3 MHz), fringe counting electronics to separate each laser beat frequency, and laser tunability. So far single mode beat frequency is achieved up to ~2 MHz without large reduction of laser oscillation power.

The interference signals detected are separated electronically at different frequencies, as shown in Fig. 6, and then introduced into phase comparators for phase measurement. In order to simulate mechanical vibration the retroreflector was modulated by means of an electromagnetic modulator seen in Fig. 4. The amplitudes of the vibration measured by two color interferometer are the same within the accuracy of the phase counter to be about 0.26 mm (Fig. 7). The two color FIR laser work was confirmed to be successful in the demonstration of mechanical vibration compensation.

In plasma diagnostic application, further optimization of the system components are needed, such as the size of a hybrid output coupler of the FIR laser cavity suitable for both wavelengths, feedback control system for two color laser oscillation, and so on.

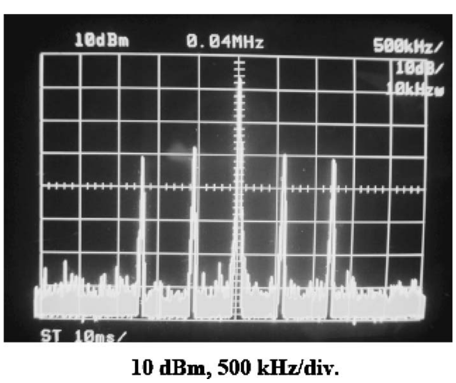

FIG. 5. Two color beat signals detected by the gallium-doped germanium photoconductor. The spectrum analyzer trace shows two color beat signals corresponding to a 57.2 μm beat of 0.55 MHz and a 47.6 μm beat of 1.2 MHz.

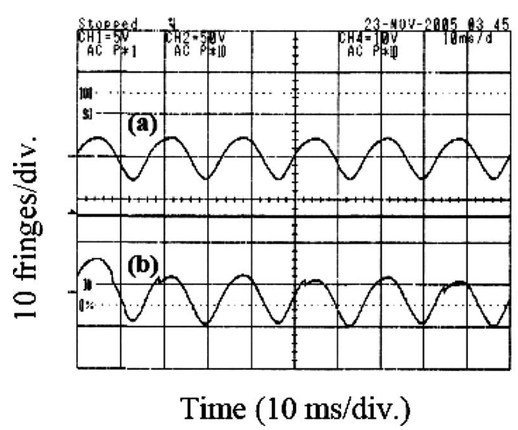

FIG. 7. Results from the two color laser interferometer. (a) Phase shift vs time. (a) 56.2 μm interferometer and (b) 47.6 μm interferometer. The mechanical vibration is simulated by using an electromagnetic modulator.

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