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Doppler frequency up conversion of electromagnetic waves in a slotline on an optically excited silicon substrate

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The Doppler frequency up conversion of microwaves in a slotline on an optically excited silicon substrate was experimentally observed. An array of 24 optical fibers with different lengths was used to effectively tilt the wave front of a 532 nm neodymium-doped yttrium aluminum garnet laser beam with a pulse duration of 33 ps. The tilted laser beam produced electron-hole surface plasma whose boundary moved at a relativistic velocity of about $c/3.4$ (c is the speed of light) along the slotline. The experiments showed that microwaves reflected at the moving boundary of the plasma in the slotline are converted to millimeter waves with a frequency up conversion ratio of 3.82. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3095846]

The frequency up conversion of electromagnetic waves scattered from the moving boundary of a stationary dielectric or conductive medium has been discussed by many authors as a potential method for generating intensive high-frequency electromagnetic waves.[1–4] In 1978, Lamp *et al.*[5] theoretically predicted that a Doppler shift occurs in the case of a moving overdense ionization front produced by short laser pulses in gaseous media. Since it is difficult to produce such boundaries in practice, so far only experiments focusing on underdense ionization fronts have been reported.[6–9] However, the operation principle of the frequency up conversion used in those experiments is not the Doppler effect but plasma effects affecting the electromagnetic waves.[10]

In 1995, Mu *et al.*[11] reported that a microwave pulse was shortened via the Doppler effect when using a moving boundary of electron-hole (e-h) surface plasma generated optically in a GaAs substrate coplanar strip line. In the frequency conversion, a moving plasma boundary is produced by a laser beam with a tilted wave front, as shown in Fig. 1. The conductive plasma short circuits a transmission line on a semiconductor substrate, reflecting incident waves and up shifting their frequency.

Generally, e-h surface plasma boundaries have advantages over ionization fronts, such as compactness and lower laser energy requirements, with respect to the generation of high-density plasma. In addition, recent progress in femtosecond laser technology paved the way for the generation of e-h plasma with sharp boundaries, which are required for efficient conversion. Therefore, frequency conversion using e-h plasma boundaries could theoretically be used as compact and convenient terahertz sources with high power and high frequency tunability. However, there have been no experimental reports on this idea since the report by Mu *et al.* As a result, the operation principle itself has not yet been fully verified. In this letter, we present experimental results which clearly demonstrate Doppler frequency up conversion realized by using e-h plasma on a silicon substrate at millimeter wavelengths.

Figure 2 shows the experimental configuration for Doppler frequency up conversion of microwaves to millimeter waves. The input microwave frequencies are between 9 and 18 GHz and the expected output frequencies are between 40 and 80 GHz. An optical fiber array is adopted in order to effectively tilt the wave front of the laser beam. The fiber array consists of 24 multimode optical fibers whose length and pitch increase stepwise by 8.3 and 1.2 mm, respectively. The laser is a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser with a wavelength of 532 nm, which generates output pulses with duration of 33 ps with a repetition rate of 10 pps. The laser pulse energy is about 0.85 μJ per fiber. The laser beams from the fiber array generate a plasma boundary moving at a speed of about $0.34c$, where c is the speed of light in vacuum.

Furthermore, the transmission line is a slotline with a gap of 145 μm and a length of 40 mm which is fabricated on a silicon-on-insulator (SOI) plate with a thickness of 150 μm. The measured relaxation time of free carriers optically generated by the Nd:YAG laser in the SOI is about 630 ps, which is long enough to ignore the carrier relaxation effect on the frequency conversion. The optical fiber array is placed at a distance of 1 mm from the surface of the slotline. The measured diameter of the laser beams at the slot surface is about 200 μm, which fully covers the slot gap. A rectangular metal waveguide is used as a high-pass filter for separating the input microwaves and the output millimeter waves.

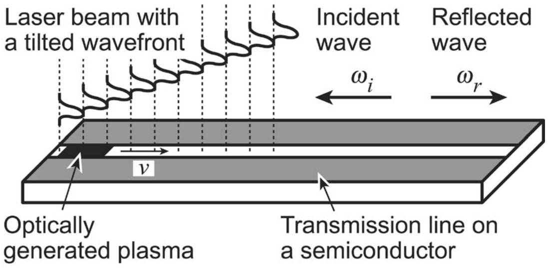

FIG. 1. Schematic of the principle of coherent scattering of electromagnetic waves from a moving e-h plasma boundary in a transmission line fabricated on the surface of a semiconductor substrate.

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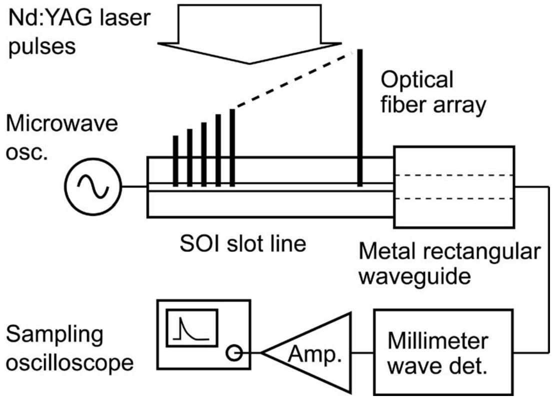

FIG. 2. Block diagram of the experimental apparatus.

Three standard waveguides at the *V*-, *E*-, and *W*-bands with different cutoff frequencies of 39.9, 48.4, and 59.1 GHz, respectively, were used in the experiments.

In Fig. 2, the microwaves from the oscillator propagated in the slotline and were completely reflected at the waveguide and were then reflected again in the optically generated plasma regions. The input power of the microwaves was between 0.65 and 1.2 W, which changed depending on the frequency. The output millimeter waves passing through the waveguide were measured by using a Schottky barrier diode (SBD) detector connected to a sampling oscilloscope (Agilent Technology, 86100A and 86112A). The response time for the output signals was about 200 ps, which was measured by the SBD detector with a 50 Ω termination (Millitech Inc., DPX-15).

Figure 3 shows the oscilloscope trace of the output signals from the SBD detector for input frequencies of 10.6, 12, and 18 GHz. The *V*-band waveguide was used in the experiment and therefore the measured signals were millimeter waves at least at frequencies above the cutoff frequency of 39.9 GHz.

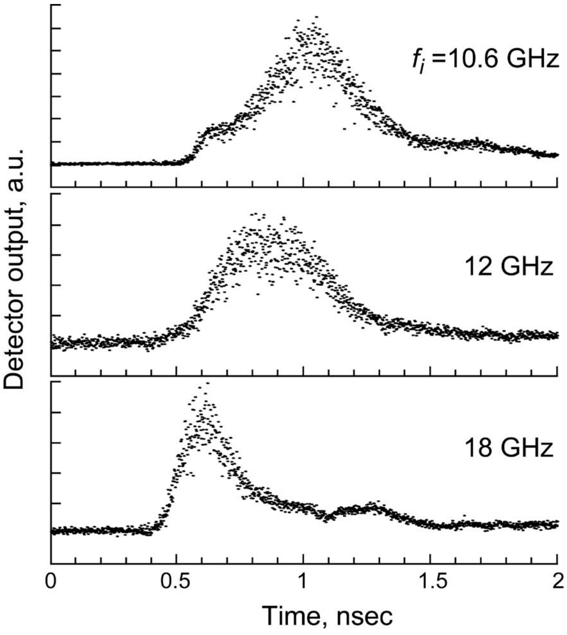

FIG. 3. Oscilloscope traces of the output signals from the SBD detector for different values of the input frequency f_i.

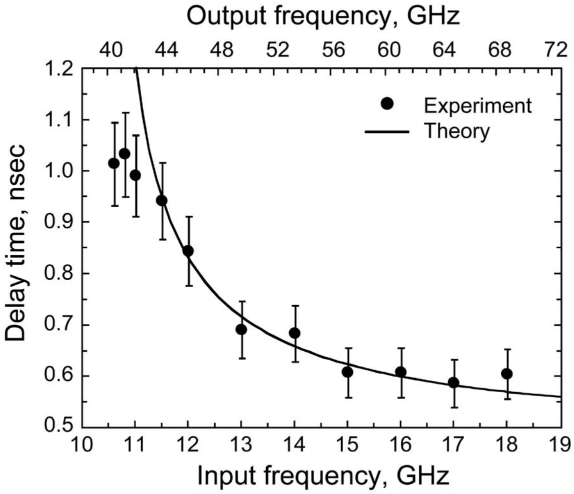

FIG. 4. Measured delay times as a function of the input frequency. Continuous curve represents the theoretical fit to the measurement values.

As seen from Fig. 3, when the input frequency was changed from 18 to 10.6 GHz, the time at which the output pulse reached the peak was delayed from 0.6 to 1.0 ns and the pulse width was broadened. The shortest measured pulse width was about 200 ps at 18 GHz, which is longer than the 113 ps estimated on the basis of theoretical considerations for the total interaction time of the microwaves in the optically generated 24 plasma regions in the slotline. This discrepancy in the pulse widths is due to the slow response of the SBD detector. On the other hand, the fluctuations in the delay time and the pulse shape are the result of the frequency dispersion of the *V*-band waveguide. In a metal waveguide with a cutoff frequency f_c, the group velocity v_g of the propagation waves is given by the equation, $v_g = c\sqrt{1-(f_c/f_r)^2}$, where f_r is the frequency of the propagating waves. It is seen from the equation that the group velocity of the output millimeter waves in the *V*-band waveguide increases as f_r increases, and thus the delay time decreases.

The output frequencies were estimated from the dispersion of the metal waveguide. Figure 3 shows the delay times for different input frequencies measured by using the *V*-band waveguide with a total length of 97 mm. The solid curve represents the best theoretical fit to the measured values calculated by assuming a frequency up-conversion ratio of 3.82 and a constant delay time of 172 ps in the detector response. The estimated output frequencies are indicated on the upper horizontal axis in Fig. 4.

In Fig. 4, the theory explains well the measured fluctuations in the delay time with an output frequency f_r, except for frequencies lower than 42 GHz. The output waves for f_r values close to that of f_c suffer strong rf loss in the waveguide,[12] and therefore the main frequency components are lost. As a result, the delay times deviate from the theoretical dispersion curve. In addition, the shapes of the output pulses were distorted, as is clear from the results for an input frequency f_i of 10.6 GHz, i.e., for f_r=40.5 GHz in Fig. 3. From Fig. 4, it is also seen that frequency dispersion clearly occurs at f_r values up to 49 GHz. This is the reason behind the broadening of the pulse width for f_i=12 GHz, i.e., for f_r=45.8 GHz in Fig. 3.

Figure 5 presents the output signal voltages measured by using three different waveguides of the *V*-, *E*-, and *W*-bands

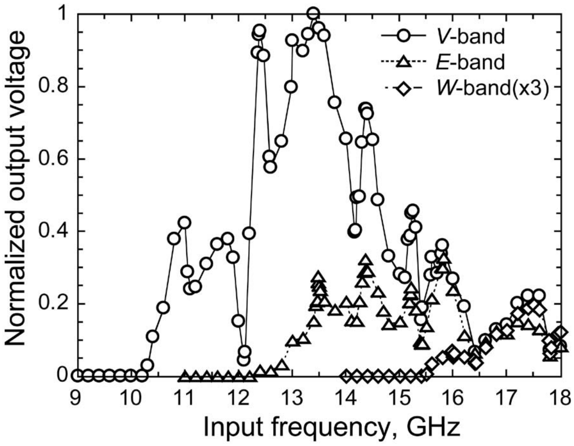

FIG. 5. Output signal voltages as measured with the SBD diode detector as a function of the input frequency for three different waveguides at the *V*-, *E*-, and *W*-bands. Signal voltages are normalized to the maximum value of 150 mV for the *V*-band waveguide at 13.5 GHz. Measured values for the *W*-band waveguide are multiplied by 3.

as a function of the input frequency. The output signals begin to appear at different input frequencies, in particular 10.3, 12.4, and 15.5 GHz for the *V*-, *E*-, and *W*-band waveguides, respectively. These frequencies might correspond to output frequencies which are very close to the cutoff frequencies of the waveguides used in the experiments. Thus, the frequency up-conversion ratios can be estimated to be 3.87, 3.9, and 3.81 for the three input frequencies, respectively. These up-conversion ratios are in agreement with the previous ratio of 3.82 within an experimental error of 2%. The measured results for the three waveguides confirm the validity of the discussion regarding the delay times shown in Fig. 4. Those results indicate that the microwaves were successfully converted to millimeter waves in the slotline with a frequency up-conversion ratio of 3.82.

The maximum signal voltage measured in the SBD detector was 150 mV for the *V*-band waveguide at 13.5 GHz. The corresponding power of the output wave was estimated to be about 0.6 mW when only the sensitivity of the detector-amplifier system was taken into account. The main reason for the low output power is the length of the laser pulses used in the experiments. As mentioned before, the interaction time of the microwaves in each plasma region is less than 5 ps. This reflection time in the plasma region is much shorter than the laser pulse duration of 33 ps. Therefore, the microwaves are reflected in a low density, growing plasma. The theoretically estimated power reflection coefficient of the microwaves is about 1%, even though the laser pulses we used have a high energy density of 2.7 mJ/cm^2 in the slotline and thus can produce plasma density of more than $10^{19}/\text{cm}^3$. Theoretical analyses performed previously by our team suggested that laser pulses with a duration of less than 1 ps are needed in order to achieve conversion efficiencies higher than 50%.[13] However, the main purpose of this experiment was to verify the operation principle of the Doppler frequency conversion rather than to achieve high output power.

In conclusion, we observed the Doppler effect in the planar slotline on an optically excited SOI substrate. The microwaves were up converted to millimeter waves with a frequency up-conversion ratio of 3.82. The results indicate that the Doppler effect can be employed to explain the operation principle of not only electron beam devices, but also solid state devices. These experimental results can contribute to the development of new types of solid state devices that operate beyond the frequency limitations of conventional solid state devices.

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