Photomixing in Resonant Laser-Assisted Field Emission—A New Technique for Wide-Band-Tunable Terahertz Sources

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***Abstract*—When optical radiation is focused on a nanoscale field emitter tip, the potential and emitted current follows each cycle of the radiation field. Nonlinearity causes mixing of the optical radiation from two lasers so that current oscillations from dc to over 500 THz can be created at the tip. Several different methods are considered for coupling these signals directly from the tip, while avoiding losses from shunting by the anode capacitance, and prototypes are described that use two of these methods. Analyses, which are consistent with measurements of the current oscillations in field emission that are caused by a transistor–transistor logic amplitude-modulated laser diode, show that this technique offers promise as a new method for wide-band-tunable terahertz sources.**

***Index Terms*—Photomixing, photonics, terahertz.**

I. Introduction

A RECENT summary of terahertz technology [1] states that "the most difficult component to realize in the submillimeter-wave bands has been the terahertz source," and gives fundamental reasons for this difficulty. Another summary [2] states that "The submillimeter-terahertz range poses unique problems in developing practical tunable oscillators. Microwave, physical electronics techniques are difficult to extend beyond 200 GHz and quantum electronics optical techniques are difficult to extend longer than 30-μm wavelengths." Above 100 GHz, solid-state devices are limited by resistive losses, reactive parasitics, and transit times that cause a high-frequency rolloff, while vacuum tubes are limited by the effects of physical scaling and metallic losses.

One popular method to generate wide-band-tunable terahertz radiation is difference frequency generation by photomixing (optical heterodyning) in low-temperature-grown (LTG) GaAs [3]–[5]. The radiation from two lasers is focused on the active region of the semiconductor at the driving point of an antenna, and photoconductive mixing causes the antenna to radiate energy at the mixer frequency. An output power of 1 μW may be generated at 1 THz with a rolloff of $1/f^4$ at higher frequencies.

It is possible that a much greater bandwidth could be obtained by photomixing in a different environment—the surface of a nanoscale tip of a polyvalent refractory metal having a dc extraction field of 4–9 V/nm. In field emission, a strong static field bends the potential at the surface of the tip so that electrons are emitted by quantum tunneling [6]–[10]. The tip would be much smaller than the wavelength of the optical radiation so the potential of the tip would rise and fall to follow each cycle of the incident radiation. Field-emission current follows the instantaneous electric field with a delay $\tau < 2$ fs [11], and the current–voltage behavior is highly nonlinear. Thus, by shifting the frequencies of two lasers that are focused on a nanoscale tip, a mixer current at the difference frequency could be tuned from dc to over 500 THz ($1/\tau$). In this technique, the limitations on the usable bandwidth are set by the methods that are used to couple to these current oscillations, instead of the fundamental processes that generate the mixer current.

The rationale for considering photomixing in resonant laser-assisted field emission as a new terahertz source is supported by the following argument. The high-frequency rolloff of $1/f^4$ that is found when photomixing in LTG GaAs is the result of a factor of $1/f^2$ caused by finite carrier lifetime in the semiconductor and a second factor of $1/f^2$ from capacitive shunting in the active region [4]. By contrast, photomixing in laser-assisted scanning tunneling microscopy (STM) has a rolloff of only $1/f^2$ because there is no semiconductor, but the tip is tightly coupled to the sample [12]. It is reasonable to suppose that, by moving the sample away from the tip in an STM, for laser-assisted field emission, the capacitive shunting would be made negligible to cause the device to have a relatively flat frequency response. Quantum simulations of photomixing in resonant laser-assisted field emission confirm the conclusion of this simple argument [10], [13].

II. Simulations of Laser-Assisted Field Emission

For radiation of low or moderate intensity, photoemission of electrons from a metal surface requires that the photon energy of the optical radiation is greater than the work function of the metal so that the electrons will be taken from the Fermi level to an energy above the potential barrier. For example, the work function of a clean tungsten surface is 4.5 eV so the wavelength of the radiation must not be greater than 276 nm. However, when there is a strong electric field, the surface potential is bent downward so that there is only a short distance in which the potential barrier exceeds the Fermi level so that electrons can tunnel from the metal by a process that is referred to as "field emission."

Fig. 1 shows the potential at the surface of tungsten without an applied field, and with applied fields of 4–9 V/nm. These potentials were calculated using the Fowler–Nordheim (F–N) model for the potential, which allows for image corrections [6], [7]. The Fermi level ε_F is shown as a horizontal dashed line in this

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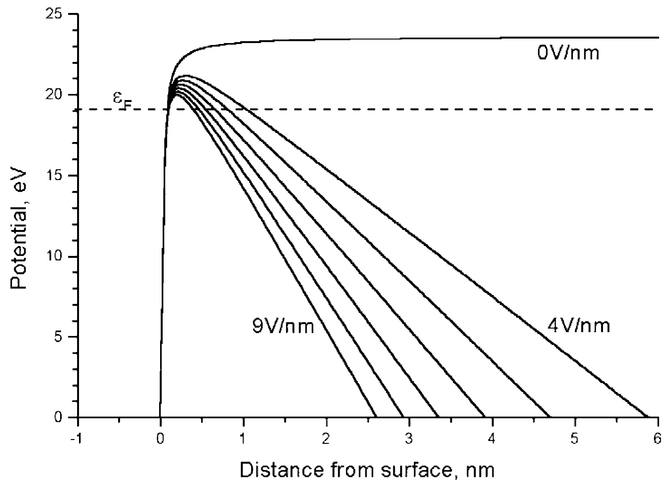

Fig. 1. Potential at the surface of tungsten.

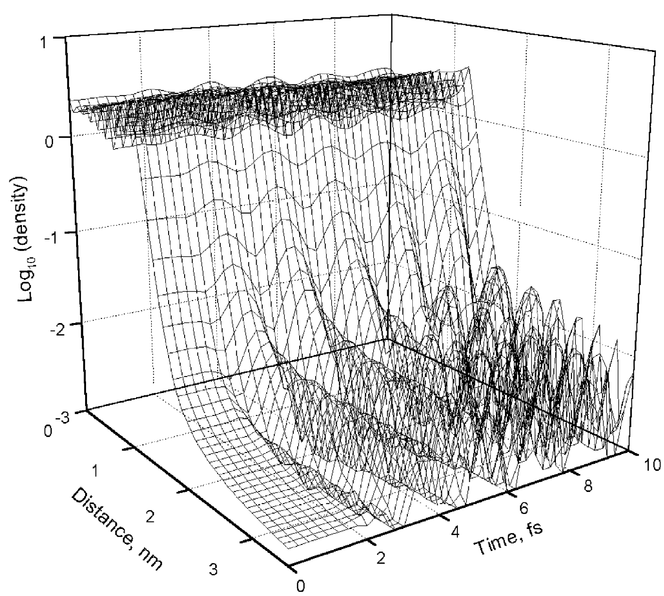

Fig. 2. Initial response of field emission to a pulsed radiation field.

figure. It is possible to understand the phenomena of laser-assisted field emission by considering the effect of superimposing the radiation field on the applied static field, i.e., both the length and height of the potential barrier will vary as a function of time, as shown on the individual curves, to cause oscillations in the emitted current.

Fig. 2 shows the initial response of the electrons near a tungsten surface to a pulsed radiation field during field emission. The logarithm of the probability density for the electrons is shown as a function of the distance from the surface and the time since the radiation field was turned on at a tungsten surface with an applied static field of 5.5 V/nm. The radiation has a wavelength of 520 nm and a power flux density of 10^{12} $\mathrm{W/m^2}$. Phenomena that are already known including the Friedel oscillations within the metal and the fall in density away from the metal surface are seen before the radiation field is present. This figure also shows that, as the height of the barrier is modulated by the radiation field, the current is increased as the barrier is lowered, and decreased as the barrier is raised. However, there is a delay of approximately 1.5 fs before the transmitted electrons have any response to the radiation field. Furthermore, there is a delay of approximately 0.75 fs between the extrema in the instantaneous value of the barrier height and the corresponding extrema in the transmission. These two delays correspond to 1.0 and 0.5 times the value of the semiclassical tunneling time, which is 1.28 fs for this problem [14]. The results that are shown in Fig. 2 were obtained by solving the time-dependent Schrödinger equation using a stable numerical procedure that was described earlier [11].

III. Photomixing in Resonant Laser-Assisted Field Emission

Rigorous simulations have been obtained using Floquet methods with density functional theory to allow for the multibody effects of exchange and correlation [15], as well as single-photon and multiphoton processes [16]. However, a simpler procedure may also be used to obtain closed-form solutions that are consistent with the more exact methods. We begin with the F–N equation for the current density in field emission [6]–[8]

$$J = AE^2 e^{-B/E} \tag{1}$$

where E is the magnitude of the applied static field, and parameters A and B depend on the work function of the tip. If two sinusoidal fields are superimposed on the static field E_0, when the photon energy may be neglected, it is possible to obtain an adiabatic approximation for the total current density by substituting the following expression for the total applied field:

$$E = E_0 + E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t). \tag{2}$$

A Taylor series expansion of (1) about operating point (E_0, J_0) where there is only the static field E_0 gives the following expression for the current density:

$$J = J_0 + J_0\left(2 + \frac{B}{E_0}\right)\left(\frac{E_1}{E_0}\cos(\omega_1 t) + \frac{E_2}{E_0}\cos(\omega_2 t)\right) + J_0\left(1 + \frac{B}{E_0} + \frac{B^2}{2E_0^2}\right)\left(\frac{E_1}{E_0}\cos(\omega_1 t) + \frac{E_2}{E_0}\cos(\omega_2 t)\right)^2 + \cdots. \tag{3}$$

Trigonometric identities may be used to simplify (3). All terms at frequencies greater than the mixer frequency are neglected because, while they are present at the apex of a field emitting tip, they would be highly attenuated in propagation on the tip. Thus, the following expressions are obtained for the total current:

$$I = I_0 + I_D + I_M \tag{4}$$

where

$$I_D = \frac{I_0}{2}\left(1 + \frac{B}{E_0} + \frac{B^2}{2E_0^2}\right)\left[\left(\frac{E_1}{E_0}\right)^2 + \left(\frac{E_2}{E_0}\right)^2\right] \tag{5}$$

and

$$I_M = I_0\left(1 + \frac{B}{E_0} + \frac{B^2}{2E_0^2}\right)\left(\frac{E_1}{E_0}\right)\left(\frac{E_2}{E_0}\right)\cos\left[(\omega_1 - \omega_2)t\right]. \tag{6}$$

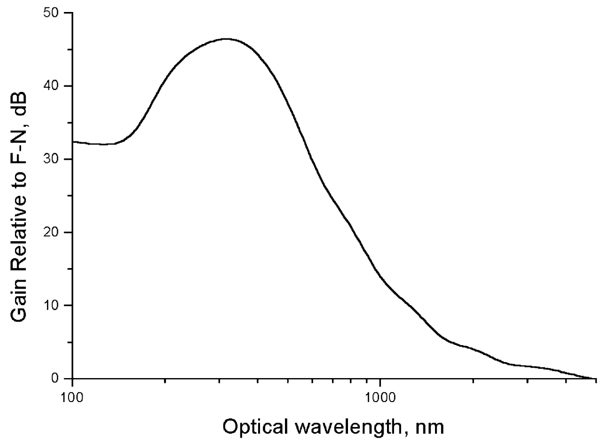

Fig. 3. Enhancement of the current caused by resonance.

Equations (4)–(6) show that the radiation field increases the dc current and also causes a mixer current. The coefficients show that these two terms are affected equally by the applied static field and the parameter B. Thus, when the two fields E_1 and E_2 are equal, the peak value of the mixer current I_M is equal to the change in the dc current I_D. Furthermore, since the two-photon processes that cause I_M and I_D are similar [16], we would expect the relationship between these two currents to be unchanged when using a radiation field for which the adiabatic approximation is not appropriate.

Equations (5) and (6) for I_D and I_M have been tested experimentally. First, the dc current–voltage characteristics were measured for five field emission tubes, and the F–N coefficients A and B were determined and found to be consistent with the work functions and sizes of the different emitting tips. Two battery-operated transformer-coupled audio signal generators were then placed in series with each tube, and the values of I_D and I_M were found to be 2–4 times greater than those calculated using the two equations. This deviation was found to be caused by the need to use relatively large values of E_1 and E_2 in our measurements, and it may be corrected by adding the fourth-derivative terms in the derivation.

When using a radiation field, instead of low frequencies where the photon energy may be neglected, the major correction to be made in the above analysis is the effects of the resonance between tunneling electrons and a radiation field [17]. This resonance, which is caused by reinforcement of the wave function through virtual photon processes, has been confirmed in recent simulations that were made by others [18]–[20]. Fig. 3 shows the gain that must be used with (4)–(6) derived using the F–N equation to correct for the effects of the resonance. This figure was generated by calculations using the data obtained from published calculations for laser-assisted field emission with tungsten [18].

IV. Techniques to Couple to the Current Oscillations

Due to the resonance, a single transistor–transistor logic (TTL) amplitude-modulated laser diode (30 mW, 690 nm) that is maximally focused ($10^6 - 10^8$ W/m^2) will cause current oscillations that can be measured with an oscilloscope [21]. This permits a direct measurement of I_D because this change in the dc current is switched on and off by the laser. Due to the small size of the tip, this effect has been used to determine the profile of the laser beam, showing that it is Gaussian. The tip acts as an antenna because the optical radiation induces an axial current that creates the time-dependent field at the apex [22]. Thus, the current is only sensitive to the component of the radiation that is polarized parallel to the axis so this effect has been used to characterize the polarization of the laser beam. The current oscillations have maximum amplitude when the center of the spot is located approximately 10 μm back on the tip from the apex. We believe that the antenna effect would be reduced with a shorter distance than this, and the decay of the induced current would be greater with a longer distance. The magnitude and waveform of the gated current have the characteristics of a low-pass filter because of shunting by the anode capacitance [23]. All of these results are found with tungsten and molybdenum tips. By contrast, with tips of carbon fiber, we found an unusually large value of I_D, but this current does not depend on the polarization and it falls off more rapidly with increasing modulation frequency [24]. These observations caused us to conclude that there is only a thermal effect with carbon fiber tips.

In one experiment, a laser diode (30 mW, 690 nm) was TTL amplitude modulated at 1 kHz and focused for an incident power flux density of 7.1×10^6 W/m^2 at the location of the tungsten tip. The applied static field was 3.7 V/nm, and the observed increase in the dc current caused by the laser $I_D = 1.75 \times 10^{-5}\ I_0$ [21]. Using (5) with $B = 65.2$ V/nm for tungsten [9], and $E_1 = 7.3\times10^4$ V/m corresponding to the measured power flux density, we would predict that $I_D = 3.4 \times 10^{-8}\ I_0$. However, Fig. 3 shows that this value of current should be multiplied by 28 (29-dB gain in the current) to correct for the effects of the photon processes at a wavelength of 790 nm. Furthermore, the optical radiation was incident normal to the axis of the tip so the local radiation at the surface of the tip is 3–15 dB greater than that in the incident beam [22], which corresponds to an increase in the current by a factor of 2–32 because the current is proportional to the power flux density. Thus, we would predict that the ratio I_D/I_0 is between 1.9×10^{-6} to 3.0×10^{-5}, and this interval contains the observed value of 1.75×10^{-5}. As yet, we have not repeated these measurements using different angles of incidence with the lasers or different optical wavelengths.

The relationship between I_D and I_M shows that if two lasers had been used, a mixer current having a peak value of $3.5 \times 10^{-5}\ I_0$ would be generated. However, this mixer current would not be seen in the external circuit because of shunting by the anode capacitance [23]. It is for this reason that we have considered several methods for coupling the mixer signal directly from the tip to a load [25]. In each of these methods, the signal is coupled from the apex of the tip by TM surface waves that are created by the current oscillations. Sommerfeld surface waves propagate on a bare metal tip [26], and Goubau surface waves propagate on a tip that is coated with a dielectric [27]. Maxwell's equations require that the current oscillations create an azimuthally directed magnetic field, which generates a radial electric field and a weaker axial electric field to form the TM surface wave. The power in the surface wave is given by $P_M = (1/2)\ Z_0 I_M^2$, where Z_0 is the characteristic impedance of tip acting as a transmission line. The signal may be coupled by (1), extending the tip to propagate the surface wave to the

load, by (2), forming antennas on the tip so that the current in the surface wave causes radiation to the load, or by (3), attaching dielectric waveguide to the apex to propagate the surface wave to the load [25].

Equation (6) may be used to derive the following expression for the power in the mixer signal that is coupled by the surface wave:

$$P_M = \frac{2\mu_0}{\varepsilon_0}\left[1 + \frac{B}{E_0} + \frac{B^2}{2E_0^2}\right]^2 \frac{I_0^2 Z_0 P_1 P_2}{E_0^4}. \qquad (7)$$

Here, μ_0 and ε_0 are the permeability and permittivity of free space, and P_1 and P_2 are the power flux densities at the surface of the tip, which may be obtained by correcting the incident values for the two lasers by using the gain from Fig. 3 and the gain caused by the antenna effect of the tip [22]. Tungsten tips may be used at current densities up to $10^9\ \mathrm{A/m^2}$ in steady state, and $10^{12}\ \mathrm{A/m^2}$ with microsecond pulses [9], where $E_0 = 4.7$ and 8.6 V/nm, respectively [10]. A typical value for the transverse characteristic impedance for Sommerfeld or Goubau TM surface waves is 500 Ω [25].

As an example of calculating the coupled mixer power, consider photomixing with a hemispherical tungsten tip having a radius of 100 nm. Two lasers, each producing an incident power flux density of $10^{10}\ \mathrm{W/m^2}$, are oriented so that the angle between the beam and the tip is approximately 15°, to provide a gain of 30 dB for each laser [22]. If each laser operates at a wavelength near 500 nm, then Fig. 3 shows that photon processes will cause a gain of 40 dB. Under these conditions, (7) shows that, at the maximum static current density, the mixer signal would have a power of 14 μW in steady-state operation, or 140 mW with microsecond pulses. Once this signal is coupled to the tip as a surface wave, it may be propagated on the tip to the load, radiated to the load by antennas formed on the tip, or coupled to the load by a dielectric waveguide attached to the tip [25]. We acknowledge that a loss of 5–10 dB/cm would occur as the surface wave propagates on the tip so the usable output power would be less than the values that we have calculated.

V. Microwave Prototypes

In the microwave prototype that is shown in Fig. 4, two stable narrow linewidth tunable lasers such as external cavity diode lasers or distributed Bragg reflector (DBR) laser diodes are focused on the apex of the molybdenum field emission tip. The frequencies of these two lasers are offset by a frequency difference that is equal to the frequency that is chosen for the output, and the laser-generated current oscillations at the difference frequency create a TM surface wave that propagates on the tip. The surface wave is transformed to a coaxial output with 50-Ω characteristic impedance by the coaxial horn transition that is mounted on a subminiature A (SMA) coaxial feedthrough connector at the wall of the tube. This tube does generate microwave radiation from 1-10 GHz, but the dc field emission current is unstable, thus, the output power is typically somewhat less than 1 μW and occurs in bursts that last for only a few seconds at a time. Generally, field emitter tips are heated before each use to

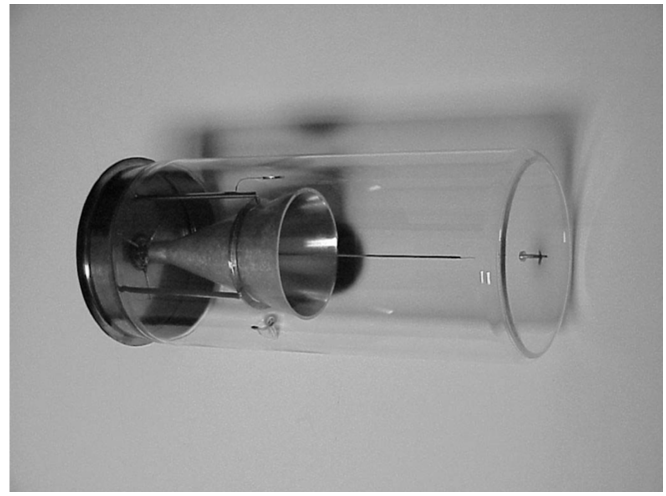

Fig. 4. First microwave source using photomixing in resonant laser-assisted field emission.

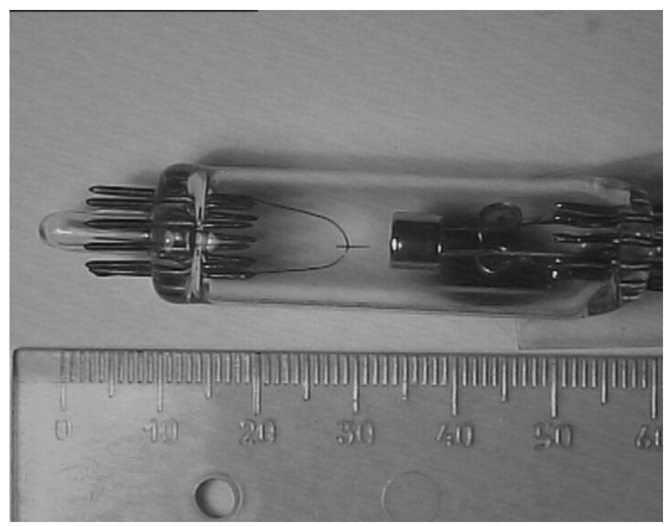

Fig. 5. Microwave prototype using a looped filament for cleaning the tip and also serving as an antenna to couple the mixer signal to the load.

clean the surface of contaminants in order to stabilize the current, but in this design, the extended tip is too large to be cleaned by heating. Furthermore, it was not possible to provide a filament for heating the tip in this design without disturbing the surface wave.

We are exploring other means to directly couple the mixer signal to the load [25], and examining tips that do not require cleaning, for the next generation of photomixers. For example, Fig. 5 shows another microwave prototype in which the tip is mounted on a looped filament for cleaning, and this filament also serves as an antenna so that the current in the surface wave will cause radiation to the load. Thus far, we have generated relaxation oscillations within the tube and measured the power that is coupled to an external dipole antenna, but this device has not yet been tested for photomixing. We are designing other prototypes that will use carbon nanotubes because carbon nanotubes are excellent field emitters, having a high current density with a relatively weak applied static field, and they work in a rather poor vacuum without requiring cleaning [28].

VI. Conclusion

Analyses that are in agreement with measurements of the current oscillations in field emission that are caused by a TTL amplitude-modulated laser diode show that this technique offers promise as a new method for wide-band-tunable terahertz sources. When compared with current terahertz devices, this technique offers the possibility of much greater bandwidth and increased output power. Furthermore, field emission is insensitive to environmental temperature, ionizing radiation, and damage by electrostatic discharge (ESD). This technique also has the potential for reduced cost because there are no high-purity components such as semiconductors, and no cryostat or femtosecond laser is required. There is also a potential for a considerable reduction in size. Field emitter arrays with 10^{10} tips/cm^2 are used in flat panel displays so that, ultimately, miniature multifunction devices could be built to implement the new technology.

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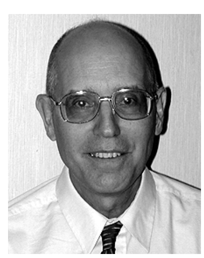

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