Equivalent Circuit for Photomixing In Resonant Laser-Assisted Field Emission

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Abstract

Resonant Laser-Assisted Field Emission is a new technology for wide-band tunable and pulsed terahertz sources. Microwave prototypes have been made to demonstrate proof of concept. Equivalent circuits are developed to extend the quantum simulations to optimize designs for maximum power and bandwidth. Calculations with the equivalent circuits are consistent with the experimental data.

Summary of the new technology

Quantum simulations [1] recently confirmed by others [2,3] show that tunneling electrons have a resonant interaction with optical radiation. By means of the resonance, a TTL amplitude-modulated laser diode (30 mW, 690 nm) maximally focused ($P = 10^6$-10^8 W/m^2) at a field emitter tip causes current oscillations that may be seen on an oscilloscope [4]. When optical radiation is focused on a field emitter tip, the tip rises and falls in potential following each cycle because it is much smaller than the wavelength. The field emission current follows the instantaneous electric field with a delay $\tau \approx 2$ fs [5], and the I-V characteristics of field emission are highly nonlinear, so photomixing in laser-assisted field emission can generate current oscillations up to 500 THz ($1/\tau$). We have studied several means to couple signals from these current oscillations [6].

Development of an equivalent circuit

The Fowler-Nordheim equation for current density in field emission is used in order to obtain closed-form expressions [10,11]. The current density is given by the following expression, where E is the electric field and parameters A and B depend on the work function of the tip.

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

The response to a time-dependent field is found by setting

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

where E_0 is the static field and the other two terms may represent the radiation. A Taylor series expansion of Eq. (1) about operating point (E_0, J_0) where there is only the static field E_0 gives the following expression for the current:

$$I = I_0 + I_D + I_M \tag{3}$$

$$where\ I_D = \frac{I_0}{2}\left(1+\frac{B}{E_0}+\frac{B^2}{2E_0^2}\right)\left[\left(\frac{E_1}{E_0}\right)^2+\left(\frac{E_2}{E_0}\right)^2\right] \quad (4)$$

$$and\ I_M = I_0\left(1+\frac{B}{E_0}+\frac{B^2}{2E_0^2}\right)\left(\frac{E_1}{E_0}\right)\left(\frac{E_2}{E_0}\right)\cos[(\omega_1-\omega_2)t] \quad (5)$$

All terms at frequencies above the mixer frequency are neglected because they would be highly attenuated. This derivation is only valid at low frequencies where the effects of photon exchange may be neglected. However, the resonance for optical radiation [1] increases I_D and I_M by $\approx$ 40 dB while their ratio remains consistent with Eqs (4) and (5).

The three components of the current in Eqs. (3-5) are represented by separate parallel paths in the following equivalent circuit. This circuit also contains an external voltage source V_0, load and ballast resistances R_{L1}, R_{L2}, and R_b, and anode and tip capacitances C_A and C_T. The beam impedance is defined by $R_B \equiv V_{AT}/I_0$, where V_{AT} is the anode-to-tip potential with the static field E_0 at the surface of the tip. From Ohm's Law, $R_B = V_0/I_0 - R_b - R_{L1}$. It is assumed that $R_{L1} << R_B$ so the feedback of I_D and I_M through R_B may be neglected.

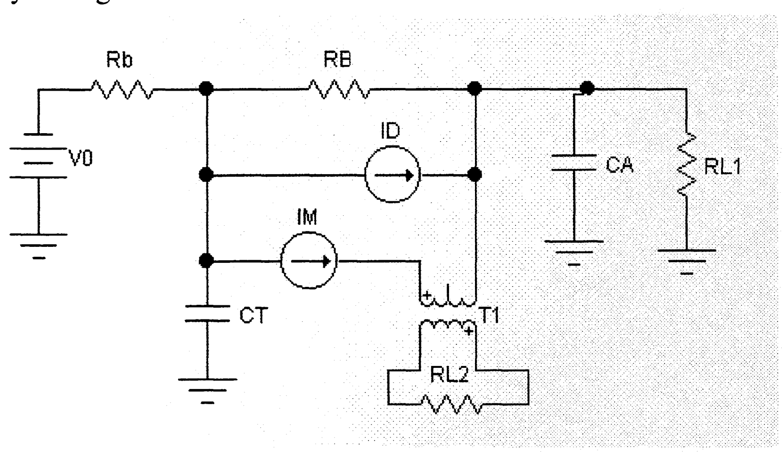

Fig. 1. Equivalent circuit for resonant laser-assisted field emission.

Application of the equivalent circuit to previous experiments

When field emission current is gated with an amplitude-modulated laser [4] the emitted current is gated at the modulation frequency of the laser, with a peak-to-peak value that is proportional to the power flux density. The magnitude and waveform of the gated current in the external circuit have the characteristics of a low-pass filter. These results are consistent with the model. For example, shunting of the current by the anode capacitance causes the external current to roll-off with increasing frequency.

Direct coupling from the tip to obtain maximum bandwidth and power

Signals may be coupled directly from the tip by (1) exciting surface waves that are propagated to the load, (2) forming antennas on the tip so the currents cause radiation to the load, or (3) exciting signals in a dielectric waveguide attached to the apex. Figs. 2

and 3 show microwave prototypes that use the first and second methods, respectively.

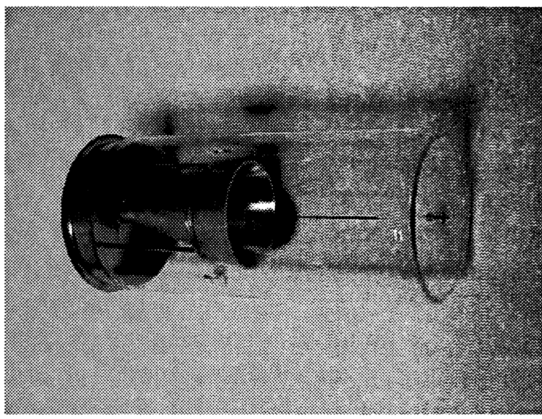

Fig. 2. First microwave photomixer using resonant laser-assisted field emission.

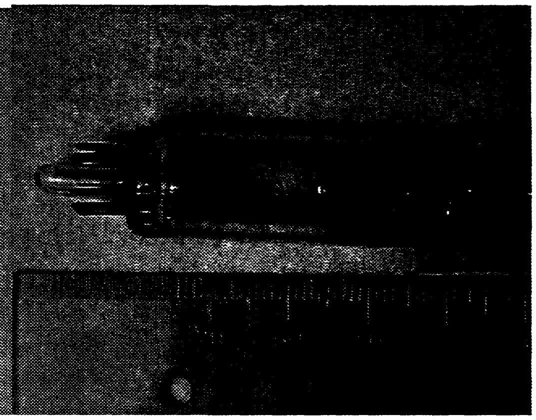

Fig. 3. Microwave source using a looped filament as an antenna.

The equivalent circuit shows how the effects of shunting by the anode capacitance, which cause the current in the external circuit to roll-off with increasing frequency, can be avoided to obtain the full bandwidth that is inherent in resonant laser-assisted field emission. At microwaves frequencies the anode and tip capacitances are effective shunts to ground, and at terahertz frequencies we need not be concerned about the impedance of the ground path return because the current is dissipated by attenuation and dispersion. The transformer in Fig. 1 represents the coaxial horn transition in the prototype in Fig. 2, transforming the surface wave to a coaxial output matched to load R_{L2}. The power propagating on the tip is approximately equal to the product of the characteristic impedance of this line and the square of the current in the surface wave:

$$P = \frac{1}{2} Z_0 I_0^2 \left(1 + \frac{B}{E_0} + \frac{B^2}{2E_0^2}\right)^2 \left(\frac{E_1}{E_0}\right)^2 \left(\frac{E_2}{E_0}\right)^2 \qquad (6)$$

Equation 6 shows that the output power is proportional to the product of the power flux densities produced at the tip by the two lasers. Using typical values for field emission, and allowing for the resonance, it appears possible to generate mW levels of power at THz frequencies by photomixing in resonant laser-assisted field emission.

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