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Ultra-wide-band pulse generation and radiation using a high T_c superconductor opening switch

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(Received 6 April 1994; accepted for publication 14 June 1994)

A new method of generating ultra-wide-band electromagnetic pulses using a $Tl_2Ba_2CaCu_2O_8$ high T_c superconductor as a fast laser activated opening switch is presented. The superconductor is used as an opening switch with a current charged transmission line pulse forming network to produce jitter-free triggered square pulses which are radiated by an ultra-wide-band conical antenna. We report radiation and reception of pulses with center frequencies near 3.5 GHz and a bandwidth in excess of 80%. We also discuss how this technique can be used to assess various wide-band antenna designs.

Recently, laser triggered photoconductive switches[1] have been developed for the generation of ultra-wide-band (UWB) pulses.[2] These switches operate as almost ideal closing switches but do not perform quite as well as opening switches due to their finite on-resistance. However, the high T_c superconductor (HTS) has recently been demonstrated as an almost ideal fast-opening, zero on-resistance, laser activated switch.[3,4]

The HTS can be transformed from its superconducting state to its normal state with a switching time of nanoseconds or picoseconds with laser pulses of various wavelengths.[5–7] When combined with a pulse-forming network, it is possible to use the HTS opening switch to generate square nanosecond electrical pulses with risetimes of less than 100 ps. These pulses serve as almost ideal step functions for excitation of an antenna. As such, they can be used to assess the time-domain performance of wideband antennas, and to produce UWB microwave radiation.[8] Furthermore, triggering of these pulses is jitter-free with respect to the laser pulse, a desirable property for the generation of UWB pulses for impulse radar applications.

In this letter we demonstrate a current charged transmission line (CCTL)[9] pulse forming network controlled by an HTS opening switch with wide-band conical monopole transmitting and receiving antennas. We also provide a subjective analysis of the pulse shape in the receiving antenna.

The CCTL pulse forming network utilized in the experiment is illustrated in Fig. 1(a). It consists of a current source charging a 50 Ω characteristic impedance transmission line (TL) through an HTS opening switch. The switch is a 50 Ω coplanar wave guide fabricated from a 0.7 μm $Tl_2Ba_2CaCu_2O_8$ film on a (100) $LaAlO_3$ substrate.[10,11] It was fastened to a cold finger in a vacuum cryogenic chamber which was cooled to 79 K with liquid nitrogen. The switch has zero on-resistance, 0.9 kΩ off-resistance, and a risetime which is shorter than the SMA connector limit (~60 ps). Since the load is typically the radiating antenna, it is placed outside the Dewar, 1 m along the TL as illustrated.

At $t=0^-$ the HTS is in its superconducting (closed) state, and the TL has charged to the current I_0. Half of the current is contained in a forward traveling wave and half in a reverse traveling wave. The net current passing through the load is zero. The HTS is then activated by a 15 ps full width at half-maximum, 20 μJ, mode-locked, Nd:glass laser pulse[12] at $t=0^+$. The laser pulse transforms the HTS to a high-resistance (open) state causing the energy stored in the TLs to be delivered to the load. The energy is delivered in the form of a pulse with a 6 ns duration corresponding to the round-trip in the 0.6 m TL to the right of the load.

The pulse delivered to a $Z_L=50\ \Omega$ resistive load is shown in Fig. 2(a). A delayed "step" is present due to the impedance mismatch which appears at the load. This mismatch would be avoidable only if the load were placed directly next to the switch inside the Dewar. Since this is impractical, the load is placed such that the round-trip time of

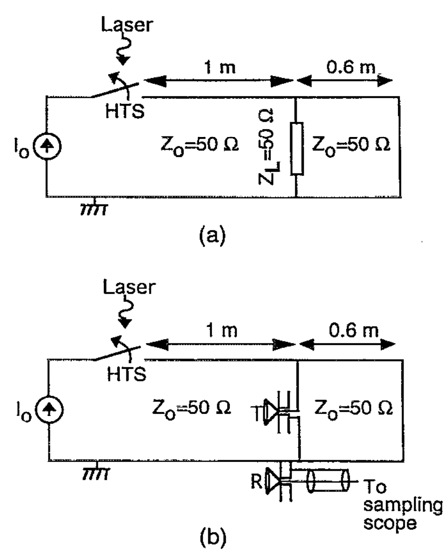

FIG. 1. (a) Current charged transmission line (CCTL) pulse forming system. The high temperature superconducting (HTS) switch is activated by a 15 ps Nd:glass laser pulse. (b) CCTL pulse forming radiation and receiving system.

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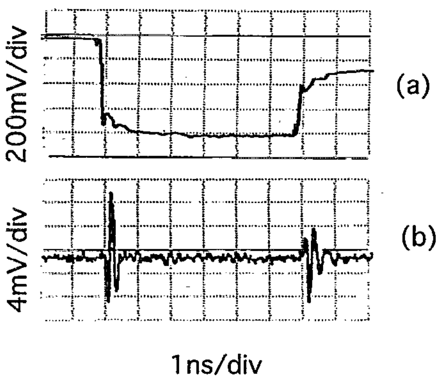

FIG. 2. (a) Pulse delivered to 50 Ω load from pulse forming system. (b) Received voltage waveform.

the line on the left is greater than the pulse width, ensuring that the "step" occurs after the pulse.

The resistive load is then replaced by a $Z_a=50\ \Omega$ characteristic impedance solid Cu conical monopole antenna mounted above a Cu ground plane as shown in Fig. 1(b). The conical antenna can be modeled to first order as a waveguide with characteristic impedance determined by the cone angle. A half angle of 47° was chosen corresponding to $Z_a=50\ \Omega$ and various cone diameters were used. A cone receiving antenna was also used, terminated in a Tektronix 11802 sampling oscilloscope which presents a matched 50 Ω load. The transmitting and receiving antennas share a common ground plane and thus a common axis. The received voltage pulse was recorded for various transmitting and receiving antenna separations and diameters.

The received pulses from the radiation and receiving system is shown in Fig. 2(b). In this case identical transmitting and receiving antennas were used, each with an end diameter of 1.9 cm and a 47° half-angle; the transmitting and receiving antennas were spaced 12 cm apart, and a charging current of $I_0=35$ mA was used. An expanded trace of the radiated and received waveform corresponding to the rising edge of the square pulse is shown in Fig. 3(a), and the power spectral density obtained from a Fourier transform of Fig. 3(a) is shown in Fig. 3(b).

The shape of the received pulse can be understood in terms of simple antenna theory. For a conical transmitting antenna which is short compared to the risetime of the driving pulse the radiated far field, $E_z^{\rm rad}(t)$ is given by:[13]

$$E_z^{\rm rad}(t+r/c)=\frac{z_0}{z_a}\frac{3a_t^2\cos(\alpha)}{4\pi rc^2}\frac{d^2V_t(t)}{dt^2}, \tag{1}$$

where Z_0 is the impedance of free space, c is the speed of light in a vacuum, Z_a is the antenna characteristic impedance, r is the field location, $V_t(t)$ is the antenna voltage at the feed point, and α and a_t are the cone half angle and length, respectively. Similarly for a short receiving antenna the voltage at the terminals, $V_r(t)$, is given by:[13]

$$V_r(t)=\frac{3a_r^2\cos(\alpha)}{2c}\frac{dE_z^{\rm rad}(t)}{dt} \tag{2}$$

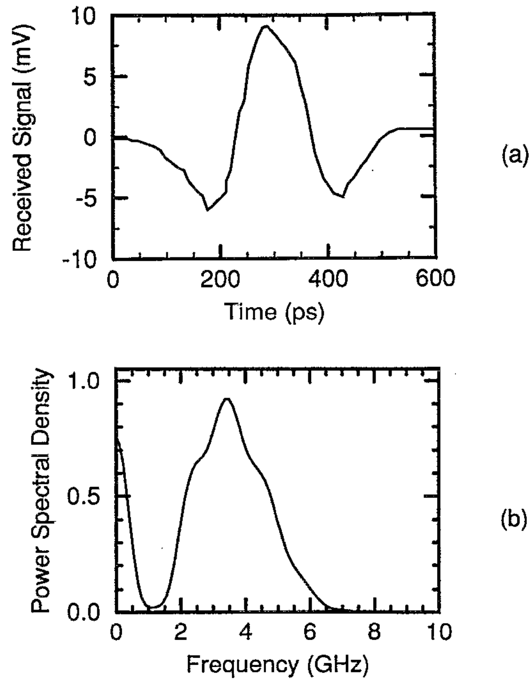

FIG. 3. (a) Expanded scale showing received pulse corresponding to the rising edge of the square driving pulse. (b) Relative power spectral density of pulse shown in (a).

where α and a_r are the receiving antenna cone half angle and length, respectively.

Thus the radiated field corresponds to the second time derivative of the driving pulse, while the received voltage corresponds to the first time derivative of the field or the third time derivative of the waveform at the input to the transmitting antenna. Since the 100 ps risetime of the driving pulse is of the same order as $2a_t/c=87$ ps for the transmitting antenna which was used, we expect the double differentiation of the transmitting antenna to be approximate in this case. The approximation is also limited by the fact that the antenna is mismatched at its feed point due to the connection of two TLs in parallel.

In Fig. 2 we see that, indeed, the shape of the received pulse corresponds to the third derivative of the driving pulse. We also experimentally verified that the received pulse amplitude scales with antenna dimension as given by Eq. (2). The $1/r$ dependence of the radiated field [Eq. (1)] was also verified to ensure that our measurements were being made in the far field. A rough estimate of the received voltage from the equations gives 7.8 mV peak which is in agreement with the result of Fig. 3(a).

Since the time domain transfer function of the transmitting antenna is proportional to the derivative of the step-function response, the frequency domain transfer function of the transmitting antenna is proportional to the Fourier transform of the received waveform, for frequencies below the reciprocal risetime of the driving pulse (1/100 ps=10 GHz). Provided that the receiving antenna is short enough to take the derivative of the radiated field, this technique can be used to assess the transfer function of a wide variety of transmitting antennas. The power spectral density of the received waveform corresponding to the rising edge of the square pulse is shown in Fig. 3(b). The plot reveals a center frequency near 3.5 GHz with a half-power bandwidth of 2.8 GHz and an 80% bandwidth, qualifying these pulses as UWB.

While conical antennas were used in this work, the HTS pulse forming technique is adaptable to other wide-band antenna designs. The system demonstrated here was limited primarily by the response time of the microwave connectors and the oscilloscope response time. However, if an integrated antenna is used with an electro-optic sampling technique, we predict that the limiting frequency will be near 70 GHz, corresponding to the rise time of the laser pulse. Thus, it may be possible to achieve a real-time measurement of antenna response with a bandwidth exceeding that of any commercially available network analyzer.

In this experiment a $Tl_2Ba_2CaCu_2O_8$ HTS was used, however, we would expect similar results if a YBCO HTS were employed instead. We also note that it is possible to significantly scale up the charging current to more than 1 A given a critical current density near 1 MA/cm^2 and reasonable coplanar waveguide dimensions.

In summary, we have demonstrated that an HTS opening switch controlling a CCTL pulse forming network and wide-band conical antenna can be used to produce UWB radiation in the 3.5 GHz regime. In addition, the step-function excitation allows one to assess the antenna transfer function directly from the received pulse. This method of generation is adaptable to a wide variety of ultra-wide-band antenna designs.

This work was partially supported by the Center for Superconductivity Research at the University of Maryland, College Park, MD. We are also grateful to J. P. Nestlerode, M. L. Schew, C. F. Carter III, and F. M. Pellicone for help in preparation of the HTS switches and to J.-F. Liang, Q. Sun, and S. E. Saddow for help in performing network analyzer measurements on our conical antennas. Helpful discussion with P.-T. Ho is also acknowledged.

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