2.C Fast, Optically Triggered, Superconducting Opening Switches

In high-power applications, opening switches play an important role. These switches are required to carry high currents (100 A–10 MA) and operate with short switching times (10 ms–10 ns). Moreover, before opening, the switch must conduct current to a parallel circuit branch (load) and withstand the voltage across the load. If there is no load in parallel to the switch, it must absorb all the energy stored in the circuit inductance. For a practical pulsed-power generator employing inductive energy storage, the opening switch has to be operated repeatedly. These diverse requirements make the design of an opening switch a challenging problem.

The existing opening switches include plasma opening switch (POS), plasma erosion opening switch (PEOS), plasma flow switch (PFS), reflex opening switch (ROS), and explosive opening switch (EOS). All these switches are used to interrupt the flow of current in the circuit. An alternative approach to the switching problems is the superconducting, inductively coupled switch (SICS), in which the load is connected to the secondary coil of the transformer while current flows through the primary. The current flow in the primary is uninterrupted. The switching is accomplished by removing a magnetic screen that isolates the secondary from the primary. This approach is particularly suited to superconducting magnetic-energy storage (SMES) applications where a persistent current is required. Since there is no switch in the storage coil (primary), there is no dissipation of energy. The number of times switches like PEOS can be operated is limited because the surface discharge degrades the source. Explosive switches are also not suited for applications requiring repetitive switch operation. The SICS has been operated up to kHz repetition rates using a train of short laser pulses, and no degradation of performance has been observed.

Part of the interest in these switches is their possible use in reducing peak electrical loads in pulsed-power systems. This may have an application in the OMEGA Upgrade charging systems.

Other types of superconducting opening switches have been investigated.[1,2] All superconducting switches involve a transition of the material from the superconducting to the normal state. The transition can be achieved by either heating the material above its critical temperature T_c, exceeding its critical current density J_c, or exceeding its critical magnetic field H_c. High-T_c superconductors appear to be superior to the metallic superconductors as material for the opening switch, as we will discuss in the next section. In our experiments, heating a $YBa_2Cu_3O_{7-x}$ (YBCO) film by laser pulses was used to perform the switching.

Principle of Operation

First we will discuss the properties of the superconducting material (YBCO) and then describe the concept of the inductively coupled switching.

1. Material Properties of the Switch

Superconducting transitions involve switching from a zero-resistance superconducting state to a finite-resistance "normal" state. High-T_c ceramic superconductors have a normal-state resistance that is orders of magnitude higher than the low-T_c metallic superconductors. An opening switch can be made by using the superconductor to shunt the load. When triggered by short laser pulses, these switches exhibit off-state resistances of the order of 100 Ω, depending on the switch geometry, and switching times of the order of 50 ns to 100 ns. These are called photoresistive opening switches.[1] The YBCO thin films have critical-current densities in the range of 1–10 MA/cm^2 and a 1-cm-wide, 1-mm-thick film will carry 0.1 kA to 1 kA of current. The high J_c makes YBCO an attractive material for the opening switch.

High-T_c superconductors are black and absorb light in the visible-near-IR range effectively. Fast heating of the film is necessary to perform the switching; this is accomplished by irradiating the film with laser pulses. Optical triggering provides accurate timing. In a current multiplication circuit using programmed inductive elements (PIE), storage inductors are charged in series and discharged sequentially, in stages that are connected in parallel with the load, through a set of isolating closing switches.[3] This circuit can be used to deliver a large load current using switches rated at a fraction of that current. The most important constraint in such a circuit is the synchronization of the opening switches with the closing switches. If the opening switches are not triggered within a short temporal window, transient high currents or voltages will catastrophically destroy the circuit elements. Optically triggered opening switches can be suitable in circuits with such constraints.

Superconductors behave as perfect diamagnets if the externally applied field is less than H_c. This means that a superconducting film in a magnetic field will expel the magnetic flux and act as a magnetic screen (Meissner effect). This property is used in our switch. In type-II superconductors such as YBCO, there exists a lower critical field H_{c1} and a higher critical field H_{c2}. When the flux penetrates the superconductor following a laser trigger, for $H_{c1} < H_{\text{applied}} < H_{c2}$, the flux reaches a stable state, and subsequent cooling of the film in a magnetic field may not exclude the flux. This may prevent the switch from operating repetitively. Primary currents in our experiments produced fields H_{applied} lower than H_{c1}. In this regime the flux penetration and exclusion above and below T_c are reversible. It is worth mentioning here that YBCO is anisotropic, and the magnetic flux screening is most effective if the field is parallel to the *c*-axis of the film. The films used in our experiments are high-quality, *c*-axis-oriented epitaxial films with J_c exceeding 1 MA/cm^2 and T_c ranging from 85 K to 90 K.[4]

Another advantage of using high-T_c superconductors as compared to low-T_c superconductors is the low cooling cost. Liquid nitrogen is sufficient as the cryogen when YBCO films are used to construct the switch.

We have found no evidence that the superconducting film degrades with repeated operation. The switches have been triggered by 150-ps pulses from a Nd:YAG laser at repetition rates up to 1 kHz. High repetition rates are limited by the switch recovery time, which in this case depends on how fast the heat can be extracted from the film.

2. Superconducting, Inductively Coupled Switch

The switch consists of a film of high-T_c superconductor placed between the primary and secondary coil of the transformer (Fig. 54.10). A similar configuration has been used for the measurement of critical current in films.[5] The film, the primary coil, and the secondary coil need not be at the same temperature. For example, in a SMES system the primary coil would be a superconducting magnet. With present technology these magnets, made from low-T_c materials, require cooling below 10 K (Nb_3Sn, T_c = 18.5 K) or with liquid helium (Nb-Ti, T_c = 9.5 K) for an optimum performance. The film can be at liquid-nitrogen temperature and the secondary coil, which is connected to the load, can be at room temperature. In our experiments, however, we used copper coils for both the primary and secondary coils and placed the film and coils inside a temperature-controlled cryostat cooled by a closed-cycle refrigerator.

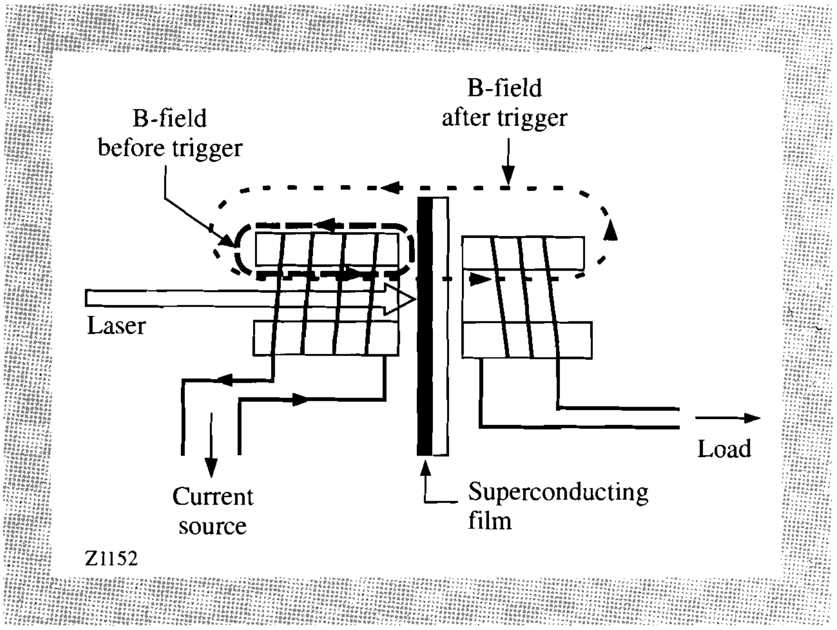

Fig. 54.10
The superconducting, inductively coupled opening switch.

In the superconducting state the film isolates the secondary coil from the primary coil. Under illumination by a laser pulse the film makes a transition to the normal state, and the magnetic flux produced by the primary current couples to the secondary coil. The temporal change of flux through the secondary coil results in an induced voltage ($V = d\phi/dt$) across the load.

In this switch there are no electrical contacts to the film. Therefore, the problem of low-resistance contacts to the high-T_c superconductor, which limits the performance of the photoresistive switch, does not arise in this design.[1,6]

Experimental Results

Some preliminary experiments have confirmed the inductively coupled switching. In these experiments, the coils were made from insulated 40 G copper wire. Since the mutual inductance drops drastically with the separation between the coils, flat, washer-shaped coils were used. Thin YBCO films, with thickness varying from 500 nm to 800 nm, were deposited on heated MgO substrates (1 cm × 1 cm) by rf magnetron sputtering.[4] The film surface was protected by a

12-μm Teflon sheet, and two identical coils were placed on either side of the sample. The inner diameter of each washer-shaped coil was 3 mm and the outer diameter was approximately 6 mm, depending on the number of turns. A 100-turn coil had an inductance of 50 μH.

The switch was mounted on the cold finger inside an optical-access cryostat. Light from a Nd:YAG laser illuminated the film. The voltage across the secondary coil was measured above and below T_c using sinusoidal input. The output voltage above T_c was found to be more than 20% of the input voltage indicating 20% coupling for identical primary and secondary coils. As the sample was cooled through the transition, the coupling decreased to less than 1%. For our samples the coupling dropped from 20% (which was found to be the same at room temperature and at the onset of transition) to less than 1% in a temperature range of 2 K. This indicates that at least 95% of the flux coupling to the secondary coil was screened by the superconducting film.

Instead of a dc current, 5-μs pulses at low duty cycle were applied to avoid joule-heating the primary. The current pulse was synchronized in time with the laser pulse such that each laser pulse arrived at the center of a current pulse. The primary current pulse serves two purposes. First, it introduces flux in the primary for a period of 5 μs and then turns it off, producing a positive and a negative voltage pulse across the secondary load corresponding to its leading and trailing edges. Above T_c these voltage pulses are indicative of the amount of flux coupled to the secondary coil and can be used to compare with the optical response. Second, it is long enough so that the optical effects take place during a time when the primary current produces a constant (dc) flux. When the film was cooled below T_c, the amplitude of these pulses was greatly reduced because of flux screening by the superconductor. We observed a voltage pulse at the load when the switch was irradiated with a laser pulse. This shows that the optical heating caused a transition of the film to the normal state and the flux to couple to the secondary coil. The amount of flux coupling varied with laser fluence (Fig. 54.11). By varying the laser fluence we were able to vary the amount of heating

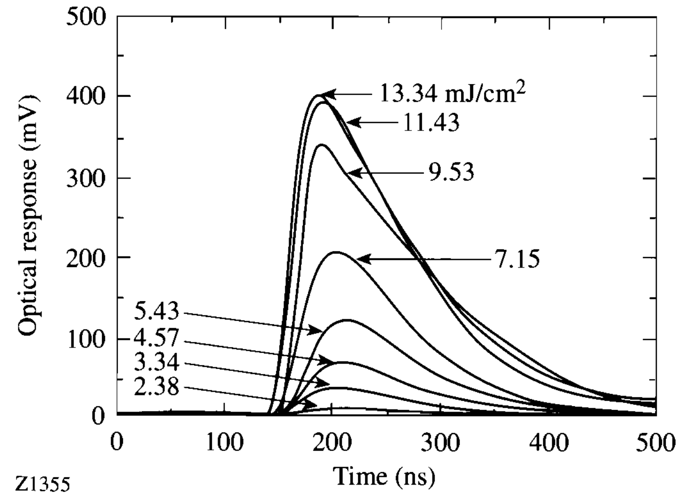

Fig. 54.11
Photoinduced switching observed in the switch of Fig. 54.10 showing the induced voltage at the secondary coil for varying laser fluence. The temperature is 76 K, and the laser trigger occurs at ≈140 ns.

of the film. The coupled flux (and hence the induced voltage) increased as the film was heated through the transition regime before saturating (Fig. 54.12). The saturation indicates that the film was fully in the normal state. The maximum induced voltage for optical triggering is approximately 400 mV. The rise times are 40 to 60 ns.

In these preliminary experiments we used the same multiturn coils for the primary coil and the secondary coil. With a 100-turn primary and a single-turn secondary, L_1 and L_2 will be 50 μH and 5 nH, respectively. The output time constant will be 5 nH/50 Ω = 100 ps. This switch is based on a derivative effect. Therefore, the output current and voltages will also be much higher, as discussed in the previous section.

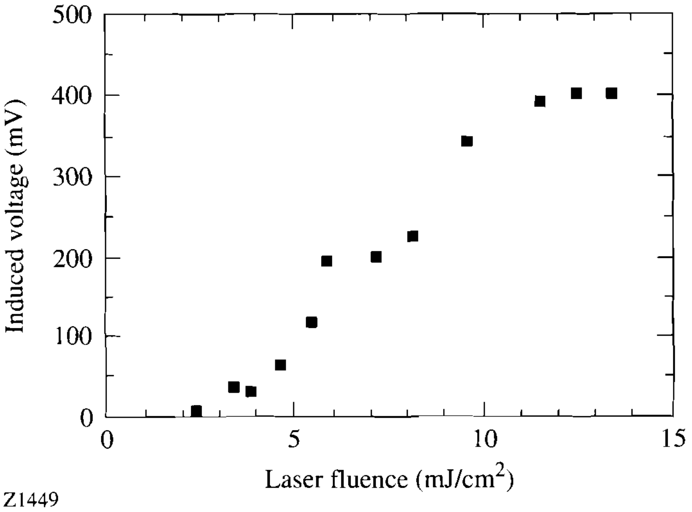

Fig. 54.12
Peak of the photoinduced voltage as a function of laser fluence. Saturation above 12 mJ/cm^2 indicates complete transition of the film to the normal-conducting state under optical illumination.

Conclusion

The superconducting, inductively coupled opening switch is a new approach to the switching problem. The superconducting film does not have any electrical contacts and acts as a flux screen isolating the load. The switch can be operated repetitively without any degradation of its performance. Optical triggering provides accurate timing and fast heating of the film. We have demonstrated the operation of this switch. The dependence of the optically induced secondary voltage on the laser fluence has been investigated. Rise times of 50 ns have been observed with multiturn secondary coils. For an optimally designed secondary coil, the switching time is predicted to be shorter, and since the switch is based on a derivative effect, the load current is also expected to be much higher.