Ultrafast Optoelectronic Interface for Digital Superconducting Electronics

Introduction

Ultrafast optoelectronics is an acknowledged field of technological importance for the 21st century, and a very large amount of research has been performed on this topic in recent years.[1] It is estimated that by the year 2006 nearly 13% of developed-world households will be connected to Global Internet via interactive broadband fiber services. This requires very high capacity networks with complex switchboards and routers. Current single-wavelength bit rates for optical fibers are between 2 and 6 Gbit/s, with laboratory demonstrations reaching speeds of up to 40 Gbit/s. Implementation of the optical wave division multiplexing (WDM) technique increases the fiber throughput to well above 1 Tbit/s. Time division multiplexing (TDM) is also an obvious, and in many aspects preferable, multiplexing choice for digital signals to increase the fiber throughput capacity. Implementation of TDM will require ultrahigh-speed transmitters in the electrical domain. Superconducting digital electronics is expected to become the processing medium of choice for these optical telecommunication applications.

The highest-speed digital data processing and manipulation can be achieved using superconducting electronics circuitry based on single-flux-quantum (SFQ) logical devices consisting of a combination of resistively shunted tunnel Josephson junctions (JJ's).[2] Low-temperature superconducting (LTS) SFQ digital circuits, fabricated in the standard, Nb tri-layer process with 1.5-μm feature size, have demonstrated clock speeds from 20 to 40 GHz. Further reduction of the linewidth to below 0.8 μm would allow JJ circuits to reach speeds of well above 100 GHz, even in complex designs.[3,4] The road map for the development of SFQ electronics estimates that high-temperature superconducting (HTS) digital circuits should reach 1-THz-range clock rates within the next ten years,[4] and, indeed, 0.7-ps SFQ pulses generated by intrinsically shunted Y-Ba-Cu-O (YBCO) JJ's have been demonstrated recently.[5]

Integrating SFQ-logic-based processors into ultrafast (e.g., above 30-GHz clock rate), high-performance applications requires, however, a new paradigm for digital input/output (I/O) communication between the SFQ processor and the outside world. Only optical fiber links can assure multi-GHz bit rates; they are also immune from crosstalk and electromagnetic interference and feature excellent thermal insulation. Together, a SFQ processor and an optical I/O will constitute the new ultrafast optoelectronics, namely superconducting optoelectronics.

This article begins with a general description of a superconducting optoelectronic router followed by, in separate sections, descriptions of progress in the development of optical-to-electrical transducers (OET's) and electrical-to-optical transducers (EOT's), suitable as I/O circuitry for superconducting digital electronics. Finally, a brief summary includes a personal assessment of the current state of the art in the superconducting optoelectronic (I/O) interface.

Superconducting Optoelectronic Router

One of the application areas where superconducting electronics can significantly outperform semiconductor technologies is telecommunication hardware, namely, ultrafast routers and crossbar-type switching structures.[4] The router is being used in telecommunication systems as the network node that directs the flow of information between different sub-networks. Figure 88.22 shows a schematic of an optoelectronic router.[6] Information arrives as multiwavelength trains of optical pulses at the router input ports, where, using suitable OET's, it is translated into the electrical domain. Next, information packages are routed to the appropriate output addresses using an ultrafast electronic processing network that provides such packet-switch functions as routing and drop/add, without the need to demultiplex down to lower data rates. Finally, signals are translated again, but this time into the optical domain, using EOT's.

In the superconducting router, the switching circuitry of the electronic information processor is based on the SFQ gates because of their very high switching speed and design simplicity. Present-day SFQ crossbar designs are limited to switching speeds below 10 GHz and utilize copper I/O microwave transmission lines.[7] These lines are known to be too dispersive and lossy at frequencies exceeding 30 GHz. They also consume too much cooling power because they constitute a cryogenic-to-room-temperature interface that accounts for up to 75% of the total load. In future-generation, 100-GHz-bandwidth routers, only optical fibers can provide the needed signal transmission bandwidth, as well as excellent thermal insulation. We note that in switching-type systems, contrary to most of the other digital data processing schemes, both the OET's and EOT's have to provide a bandwidth that is at least equal to the operating frequency of the information-processing unit. Thus, the clock rate of the entire router circuit is limited by the digital processor and *not* the I/O circuitry.

In the example in Fig. 88.22, optically coded information has the form of return-to-zero (RZ) pulses. Logical "1's" in subsequent clock cycles are coded as separate pulses, while the absence of a pulse in a given clock cycle is interpreted as logical "0." The RZ coding is optimal for laser pulses and fits naturally to the SFQ logic, which is also coded based on either presence or absence of a pulse in a clock cycle.[2] Thus, no additional matching circuitry is needed at the I/O ends. Finally, the OET's and EOT's should be optimized for a 1.55-μm-radiation range since this wavelength is the optical communication standard for data transmission.

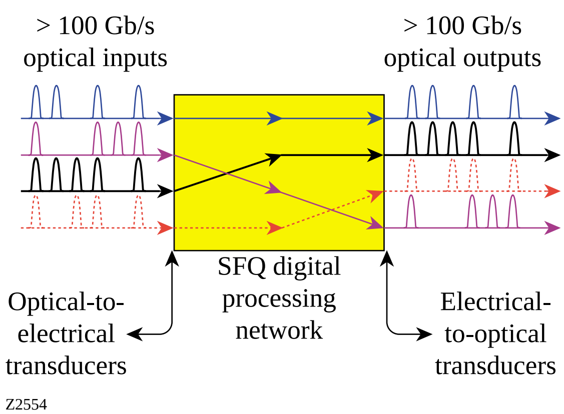

Figure 88.22
Schematic of the superconducting optoelectronics input and output interfaces for an ultrafast SFQ digital information processing network. Each train of optical pulses represents a different optical wavelength due to assumed implementation of the WDM technique.

Superconducting Optical-to-Electrical Transducers

The first superconducting optoelectronic circuit was demonstrated by Dykaar *et al.*[8,9] As shown in Fig. 88.23(a), a photoconductive metal-semiconductor-metal (MSM) diode (a 50-μm-wide gap in the coplanar line, on the left-hand side of the junction) was used as the OET, and the generated photoresponse signal was directly applied to switch a tunnel JJ. The structure was fabricated using the Pb-alloy technology[10] on a semi-insulating GaAs substrate, which acted as the active medium for the MSM switch. Since the JJ was not shunted, the circuit operated only with the unbiased junction and when the MSM-generated excitation current pulses (typically ~8 ps wide) exceeded the critical charge (time integral of the pulse) needed to switch a hysteretic JJ into the resistive state.[9] The circuit was tested using the early version of the cryogenic electro-optic (EO) sampling system,[11] with the 50-Ω probe transmission line fabricated on $LiTaO_3$ and wire-bonded directly to the superconducting coplanar line [Fig. 88.23(a)]. The JJ switching waveform was sampled about 300 μm from the junction [see "sampling point" in Fig. 88.23(a)]. The recorded transient is shown in Fig. 88.23(b).

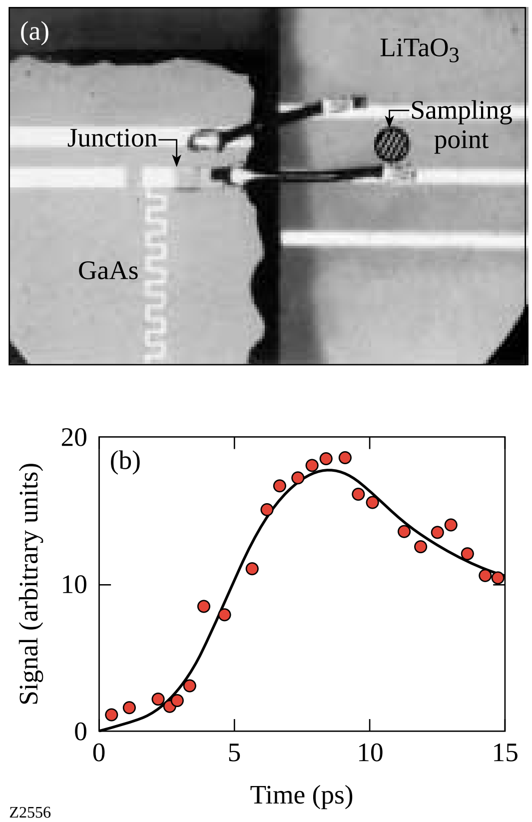

Figure 88.23
(a) Micrograph of an optoelectronic superconducting Pb-alloy circuit consisting of a GaAs photoconductive switch and separately biased Josephson junction (JJ). The circuit is wire-bonded to a transmission line on a $LaTiO_3$ crystal for EO sampling measurements. (b) Time-resolved switching process of the unbiased JJ shown in (a), driven by an 8-ps-wide electrical transient. The input amplitude was approximately five times the junction critical current. Temperature was 2.1 K.

It exhibits a ~3-ps turn-on delay time, followed by a ~5-ps rise time. The signal fall time is significantly longer, demonstrating that after switching, the junction remained in the transient voltage state, as expected from JSPICE-program numerical simulations.[9]

The usefulness of the structure shown in Fig. 88.23(a) for practical router structures was limited by the use of an unshunted JJ. The hysteretic nature of the junction current–voltage (*I*–*V*) characteristics precluded the use of the junction dc bias as an adjustable switching threshold. In addition, the junction exhibited a large resistive-capacitive (RC) time constant, limiting the transducer's speed of response. Later, Van Zeghbroeck[12] published systematic studies of *I*–*V* characteristics of various cryogenic MSM diodes and demonstrated that Nb-Si-Nb devices were compatible with Nb-based JJ circuits.

The next-generation superconducting OET system proposed and implemented by Wang *et al.*[13] was free of the limitations suffered by its predecessors. The test structures were fabricated at the HYPRES Foundry, using their standard Nb process,[14] and were fully compatible with the current SFQ digital circuit technology. This OET is shown in Fig. 88.24(a) and consists of a Nb-Si-Nb MSM photodiode, integrated with a two-JJ pulse shaper. This arrangement allowed trains of 100-fs-wide optical pulses from an external laser source, incident on the Nb-Si-Nb diode (switching beam), to be transformed into electrical signals and shaped into SFQ pulses by the two-junction Josephson pulse shaper (both JJ's were externally resistively shunted). The SFQ waveforms were recorded right after the second JJ (sampling beam), using the EO sampling system, and, as shown in Fig. 88.24(b), represented sub-mV, 3.2-ps-wide voltage transients. The integral of the experimental signal was equal to Φ_0, a quantum of magnetic flux, confirming that indeed the OET output consisted of single SFQ pulses. The measured pulse characteristics were in very good agreement with JSPICE simulations.[13] The simulations also showed that the width and amplitude of measured SFQ signals were limited by the parameters of the JJ's used in the pulse shaper and not the Nb-Si-Nb photodiode.

Wide possibilities for superconducting optoelectronic circuits[15] were opened as a result of the successful demonstration that the integrated OET system is indeed able to transform a train of optical pulses into the SFQ-coded input for a superconducting digital electronic circuit at rates of up to 30 Gbit/s for 1.5-μm-feature-size JJ technology (HYPRES standard process[14]). Currie, Sobolewski, and Hsiang[16] used Nb-Si-Nb photodiodes to inject approximately 20-ps-wide electrical pulses into Nb-based superconducting transmission lines to study their propagation properties. They also determined the amount of crosstalk between two Nb microstrips, fabricated at different metallization levels and separated by a dielectric SiO_2 layer (see Fig. 88.25). The time-resolved crosstalk signal was measured using the EO sampler and was >20 dB below the signal propagated in the main transmission line (see "sampling points" in Fig. 88.25). The results were in very good agreement with the simple capacitive model of the signal coupling between the two crossing microstrips. Bulzacchelli *et al.*[17] implemented MSM diodes for an optoelectronic clocking system in which optical pulses were delivered via fiber to a superconducting chip, on which the Nb-Si-Nb OET triggered the SFQ

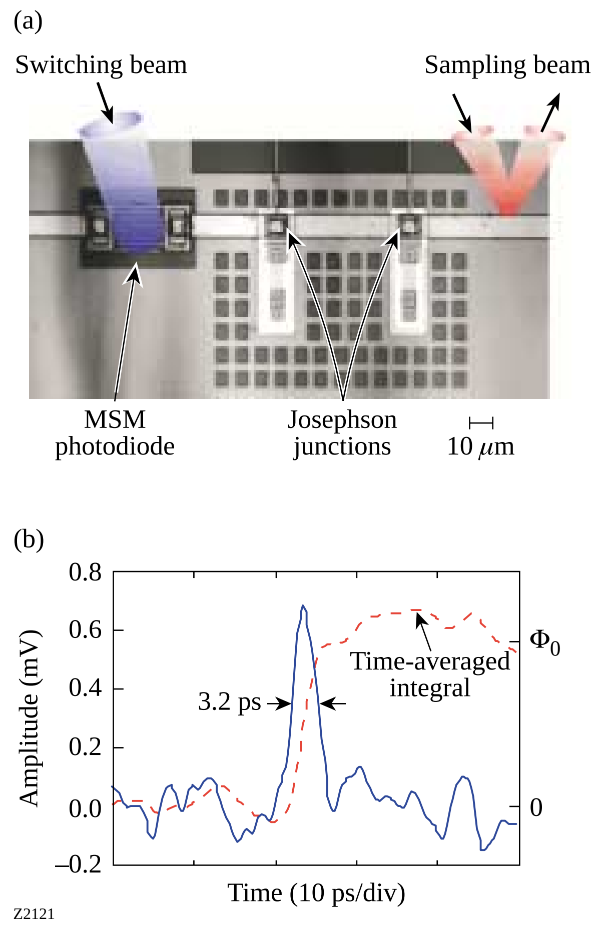

Figure 88.24
(a) Micrograph of an optoelectronic superconducting Nb circuit consisting of a Nb-Si-Nb MSM photodiode coupled to a microstrip line and followed by a two-junction pulse shaper. The entire circuit was overlayed with a $LaTiO_3$ crystal for EO sampling measurements (not shown). (b) Time-resolved single SFQ pulse and its time integral. Temperature was 2.1 K.

circuit at frequencies reaching 20.6 GHz. As in the work by Wang *et al.*,[13] all of these electronic structures were fabricated in the standard, Nb-trilayer HYPRES process.[14]

The discovery of HTS materials offered the promise that HTS digital electronics can reach terahertz clock speeds.[3,4] The characteristic response times of HTS are of the order of single picoseconds[18] and intrinsically shunted YBCO JJ's exhibit a characteristic voltage close to 8 mV,[19] predicting that the corresponding SFQ pulse width, generated during the junction switching event, should be well below 100 fs. To achieve comparable, subpicosecond electrical excitations, Osbahr *et al.*[20] used amorphous GaAs, deposited directly on a coplanar YBCO transmission line. The structure acted as a MSM diode, and the authors successfully generated the shortest 0.4-ps-wide electrical input pulses reported to date (~2-THz digital bandwidth). The pulses were used to study propagation properties of YBCO transmission structures. It is interesting that GaAs did not "poison" the YBCO; however, an overlay of Au on the YBCO strips was needed to sustain the highest, THz-frequency components in the propagating pulses. This latter result confirmed the earlier studies[21] that at above 300 GHz, microwave loss of superconducting YBCO actually exceeds that of normal metals, such as Au or Cu, kept at 77 K.

Independently of semiconducting MSM-type devices, both LTS[22,23] and HTS[18] microbridges, operated as hot-electron photodetectors, have been proposed as OET's. For LTS photodetectors, NbN was the material of choice since it is characterized by a ~30-ps photoresponse time,[24] the fastest among conventional superconductors. In the case of HTS structures, the YBCO microbridge was successfully implemented as an optoelectronic interface for switching a grain-boundary YBCO junction.[5] Figure 88.26(a) presents an integrated YBCO microbridge plus a YBCO–JJ structure. The bridge was independently biased (not shown) and, upon illumination with a femtosecond optical pulse (excitation beam), generated ~2-ps-wide electrical transients, which were then applied to switch the dc-biased JJ. Time-resolved dynamics of the junction were studied with the help of the EO sampling system (sampling beam). The actual test geometry, shown in Fig. 88.26(a), was characterized by a large inductance parallel to the JJ, due to the extended, right-angle-type junction leads. Nevertheless, the authors were able to extract the actual junction switching process and demonstrate [see Fig. 88.26(b)] that the response consisted of a train of 0.65-ps-wide SFQ pulses. The measured signal was in very good agreement with JSPICE simulations performed for a shunted JJ with the characteristic voltage of 2.1 mV. The JJ's estimated power consumption associated with the SFQ pulse generation was ~0.1 μW, leading to a "switching time" $\times$ "dissipation power" product equal to 0.08 aJ, the lowest reported value for any digital device. Further JSPICE simulations[25] predicted that YBCO JJ's with the characteristic voltage above 3.5 mV (well within the reach of the current HTS JJ technology[19]) should generate SFQ pulses with a width of <300 fs, which corresponds to a 3-dB bandwidth of >1 THz, breaking yet another "barrier" in the development of digital technologies.

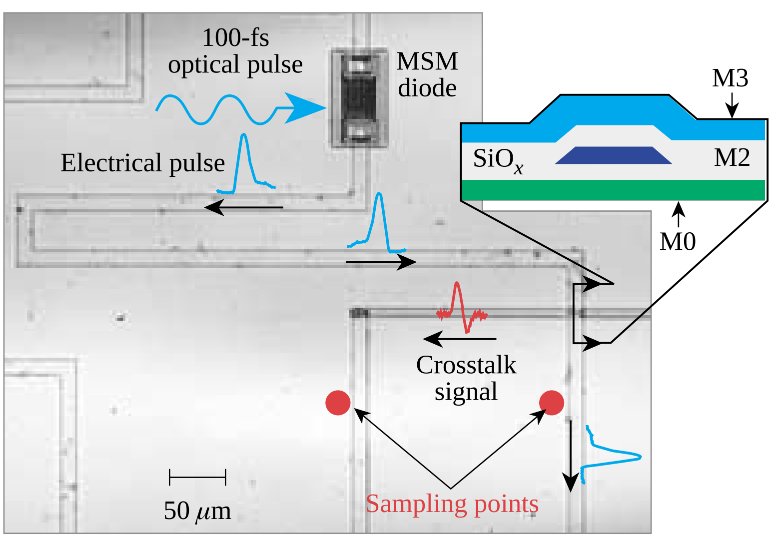

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Figure 88.25
Micrograph of an experimental setup for measuring crosstalk. The circuit uses an MSM diode to generate a picosecond electrical transient, which propagates along the main microstrip line (MSL) and then crosses above the other. At the intersection each line is on a different metallization layer. The signals on the two MSL's are detected at sampling points by the EO system.

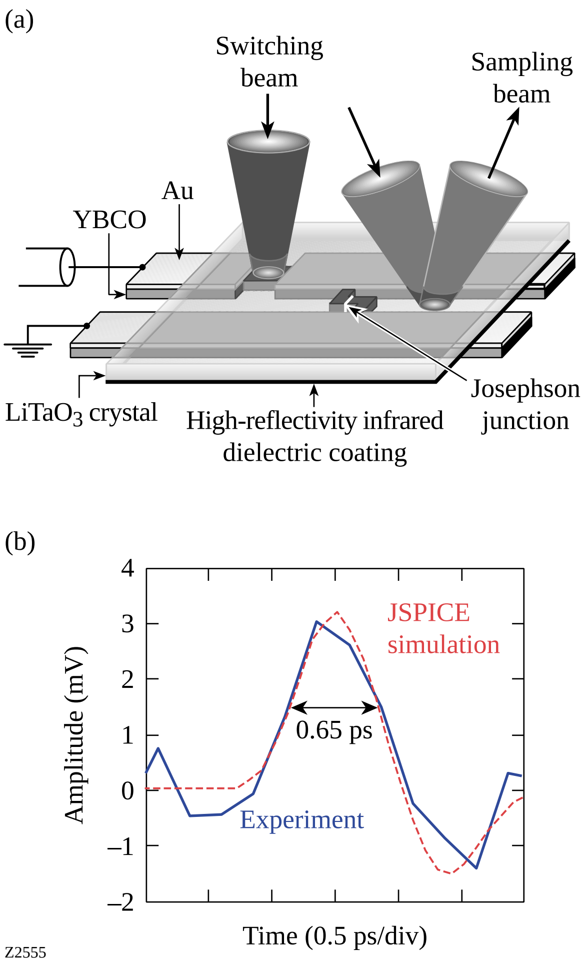

Figure 88.26
(a) Schematic of a coplanar strip transmission line containing a YBCO microbridge and a bicrystal JJ. The entire circuit is overlayed with a $LaTiO_3$ crystal for EO sampling measurements. (b) Time-resolved, single SFQ pulse and the corresponding numerical JSPICE simulation. Temperature was 20 K.

Superconducting Electrical-to-Optical Transducers

Both the OET and EOT ends of the telecommunication router must, of course, operate at the same speed. In the case of the superconducting crossbar, in the best scenario, the EOT should be able to transform a sequence of “0” and “1” SFQ pulses directly into optically coded information. The design of the SFQ-to-optical output interface is a very challenging problem, mainly due to the extremely low energy being carried by SFQ pulses, and, so far, there are no satisfactory practical solutions. Several new concepts, however, designed specifically for digital superconducting electronics, have recently been proposed.

The first optical output interface for JJ electronics was proposed by Van Zeghbroeck[12] in the form of an actively modulated GaAs/AlGaAs semiconductor laser diode with a sub-mA threshold current. The GaAs/AlGaAs laser diodes were selected because of their low power dissipation and large modulation bandwidth. The first actual implementation of the laser-diode EOT system in a JJ latching integrated circuit was achieved by Nakahara *et al.*[23] The authors used the special high-voltage Josephson circuit to increase the signal level to about 10 mV and then amplified it using a liquid-helium HEMT (high-electron-mobility transistor) semiconducting amplifier. Subsequently, the output was fed into a liquid-He InGaAsP laser. Although only low-frequency tests were performed, the expected maximum speed of the output circuitry was estimated to be approximately 1 GHz.

A laser diode operating at 4.2 K was also used by the HYPRES team[26,27] to provide a serial output data stream via an optical fiber from a superconducting analog-to-digital converter (ADC) to room-temperature conventional electronics. The output from the ADC was linearized with a parallel-to-serial converter, amplified with an on-chip driver (Josephson amplifier), and used to modulate a laser diode biased at the lasing threshold. The authors also investigated in detail the performance of various laser diodes fabricated for operation at 4.2 K.[27] They found that, at low temperatures, the current threshold for lasing reduces significantly, resulting in much lower input power being needed to operate the laser. Unfortunately, the dynamic resistance (dV/dI) also increases significantly near the lasing threshold and the power efficiency (dP_{out}/dI) decreases. To successfully operate a laser as a superconducting EOT, its dynamic resistance should be as small as possible, so that an appreciable current modulation is produced when a small voltage signal is applied. At the same time, dP_{out}/dI should be as large as possible, to get a large modulation of the optical power output. The analysis presented in Ref. 27 indicated that $dV/dI < 10\ \Omega$ and $dP_{out}/dI \geq 0.5$ mW/mA are required for robust operation of a laser-based optical output interface for superconducting electronics. More research on cryogenic laser diodes is needed to achieve these parameters.

Recently, Sobolewski and Park[28] proposed a magneto-optic (MO) modulator as an ultrafast EOT. The main advantage of a passive modulation scheme is that it requires only a sensitive medium and optimized coupling between electrical and optical signals to obtain the desired modulation efficiency and speed of response. For cryogenic systems, it is very important that fiber-coupled modulators represent only a minor thermal load. While the MO effect has been applied to optical modulators[29] in current, conventional optoelectronic systems, ultrafast EO modulators are used exclusively as EOT's. Unfortunately, the EO modulators are not practical for superconducting electronics since they require high-voltage driving signals and, thus, are incompatible with SFQ gates.

MO modulators based on the Faraday effect offer a number of advantages for superconducting optoelectronics. Many MO materials, including the most-sensitive europium monochalcogenides, exhibit MO properties only at temperatures below 20 K,[30] while the Verdet constant for diluted-magnetic semiconductors, or garnets, increases drastically at low temperatures. In addition, some MO crystals (e.g., EuS and EuSe) are characterized by <2-ps response times, assuring above-150-GHz, 3-dB analog bandwidth.[31] In garnets, the response is limited by the ferromagnetic resonance frequency (e.g., 82.3 GHz for Bi-YIG[32]) with potential for reaching >1 THz.

Figure 88.27 shows the concept of a superconducting MO modulator based on a microwave microstrip line (MSL) with a polarization-sensitive MO active medium and fiber-optic cw light delivery [Fig. 88.27(a)]. The MSL configuration, with the superconducting ground plane, allows for a long interaction distance, and the low characteristic impedance of the line assures that the *H*-field component of the electromagnetic signal is uniform along the modulator length [Fig. 88.27(b)]. Light modulation direction occurs in parallel to the *H* field and perpendicular to the signal propagation. Unlike most common EO modulators, this eliminates the need to match the velocities of the electromagnetic signal and light, unless a multipass design is considered. Numerical simulations showed that for the 100-μm-wide, 5-μm-high MSL, filled with the EuSe MO material and assuming that the input current pulse is 1 mA (10-kA/cm^2 critical current density for a nominal 10-μm^2 Josephson tunnel junction), the *H* uniformity along the optical pass is >98% and the angle of Faraday rotation for green light reaches ~0.13°. In a crossed-polarizers modulator geometry, such a polarization rotation angle should give a signal-to-noise ratio of above 10 in the 160-GHz bandwidth of Ref. 33.

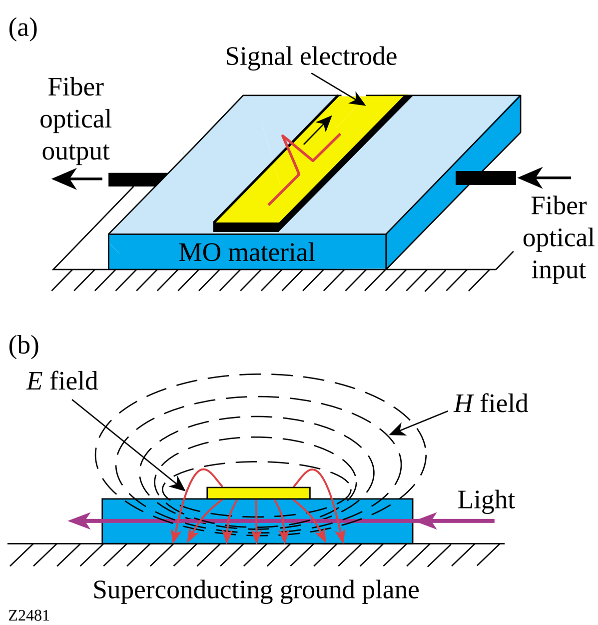

Figure 88.27
Structure of a superconducting MO modulator proposed in Ref. 28. (a) Modulator geometry. (b) Cross section schematically showing spatial distribution of the *E* and *H* fields.

Conclusion

Various concepts for ultrafast I/O interfaces for digital superconducting electronics suitable for telecommunication routers have been reviewed. For the input OET, it has been demonstrated experimentally that both the amorphous GaAs photoconductive switch and the YBCO hot-electron photodetector are able to transform the >100-Gbit/s optically coded input information to the electrical domain with sufficient signal-to-noise ratio, speed, and power loading. The Nb-Si-Nb diode is also a desired solution, primarily because of the ease of integration with the standard Nb JJ fabrication process. The Nb MSM's, however, should be patterned with deeply submicron dimensions to reach the single-picosecond response times needed for the ultrafast router applications. From the bias point of view, MSM-type structures have a significant advantage over hot-electron photodetectors since they are highly resistive in the OFF state and do not load the circuit. On the other hand, the responsivity of superconducting photodetectors is significantly higher. Most recently, NbN photodetectors have been demonstrated to respond to single visible and infrared photons,[34] making them the leading candidate for future quantum communication and quantum cryptography systems.

Optoelectronic output from the superconducting electronics and, especially, the direct SFQ-to-optical transition is very difficult since SFQ pulses carry very little energy. There is no proven concept that achieves both the needed >100-Gbit/s speed and the required sensitivity. The active laser-diode modulation scheme allows for direct modulation of the optical output at the processor clock frequency; however, for SFQ electronics, it requires substantial, broadband amplification of SFQ pulses or high-voltage latching Josephson output drivers to drive the laser. In addition, the laser itself, placed inside the dewar, is a significant source of thermal loading. Laser modulation can be a viable option in systems where the output signal has relatively low clock frequency (e.g., in digital decimation filters) since the current EOT designs are limited to speeds of approximately 1 GHz. Extensive research is needed to develop a semiconductor laser diode optimized for ultrafast performance at cryogenic temperatures.

Passive modulation schemes seem to be the approach of choice since, in the modulator case, one needs to achieve only an "imprint" of the SFQ-coded information onto the optical beam to carry it into room temperature and, subsequently, process it using conventional optoelectronics. Passive modulation, based on EO modulators, is the current optoelectronic industry standard. Among optical modulators for superconducting SFQ electronics, MO devices are favored by the author since, at least based on the literature and ultrafast sampling measurements conducted by Freedman,[31,32] they seem to be fast and sensitive enough, and their performance is actually improved at cryogenic temperatures. The first comprehensive demonstration, however, is yet to be performed.

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