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PASSIVE SUPERCONDUCTING MICROWAVE CIRCUITS FOR 2-20 GHz BANDWIDTH ANALOG SIGNAL PROCESSING*

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ABSTRACT

A new technology for making analog signal-processing devices such as linear-FM chirp filters with time-bandwidth products up to 1000 is being developed using niobium stripline on sapphire. Preliminary results of delay lines, resonators, and a 25-ns, 2-GHz chirp filter will be presented.

A new technology based on superconducting niobium stripline patterned on very-low-loss dielectric sapphire substrates is being developed for analog signal processing with bandwidths of 2 to 20 GHz. This microwave circuit technology is made possible by combining advances in microfabrication processes used in surface-acoustic-wave (SAW) devices[1] and very-large-scale integrated (VLSI) circuits, Josephson junction fabrication[2] (in particular niobium sputtering and reactive-ion etching), and dielectric substrate fabrication fostered by microwave integrated circuit (MIC) development.

Analog signal-processing filters with time-bandwidth (TW) products of 500 to 5000 can be made by suitably combining delayed replicas of the input signal. Convolvers, correlators, and real-time spectrum analyzers can be made by providing an appropriate mechanism for the interaction of two signals over their entire time duration, which again requires the capability to delay a signal. Analog discrete-time devices with bandwidths up to 20 MHz have been made with charge-coupled devices (CCDs); analog continuous-time devices with bandwidths up to 1000 MHz (1 GHz) have been made using surface-acoustic-wave (SAW) devices; and recent research effort has explored acoustooptic (A/O) devices and magnetostatic wave (MSW) devices, both with bandwidths of about 1 GHz. The propagating wave velocities in these devices are substantially below the speed of light; thus one can achieve large interaction times in relatively compact forms. However, a host of physical limitations such as propagation loss, dispersion, and transducer inefficiency[3] prevents the practical utilization of these techniques at bandwidths above 2 GHz. In contrast, electromagnetic devices are capable of extremely wideband operation. However, because of the high propagation velocities only very small interaction times are practical in conventional devices. For example, a 100 ns device would require about 30 meters of free space delay or about 10 meters if the medium had a dielectric constant of 10. This length of coaxial cable or waveguide would be physically cumbersome. Such a delay could be achieved with a copper microstrip delay line on low-loss 0.4-mm thick alumina substrate and would require an area of about 500 cm^2. However, for 5-GHz bandwidth operation centered at 10 GHz, it would have a loss of about 40 dB at room temperature. The area and loss can be traded off. In fact, conductor loss in dB is inversely proportional to the substrate area for fixed line impedance, but since the loss-area product is unreasonably large a new electromagnetic delay technology is required.

*This work was sponsored by the Departments of the Army and the Air Force.

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Fortunately the elements of a new technology have already been explored. The need for faster and more compact digital computers has resulted in a superconducting technology based on Josephson junctions using lead, lead alloys or niobium.[4] In addition, analog circuits using superconducting microwave cavity resonators or simple microstrip filters and resonators have been demonstrated.[5,6,7] The microstrip circuits have used lead or lead alloy which is fragile and difficult to pattern for linewidths less than 25 µm. These circuits have been envisioned for use in stable oscillators or similar applications requiring a simple bandpass filter with extraordinarily high Q (10^4 to 10^8).

We have demonstrated in principle that by using a rugged refractory superconductor such as niobium, which at 4.2 K has a surface resistivity of about 0.1% that of copper at room temperature, one can make very narrow microstrip or stripline microwave transmission lines and hence pack extraordinarily long delay on easy-to-handle 5-cm-diameter substrates. Figure 1 shows the stripline geometry and defines the dimensional variables. We have made lines which are 2.5 meters long, and lines which are 100 meters long are conceivable. Because stripline has insignificant dispersion and the conductor and dielectric loss are approximately independent of bandwidth, for fixed time-bandwidth product, the major bandwidth constraint is imposed by the coaxial cable and coax-to-stripline transitions at the input and output of the device.

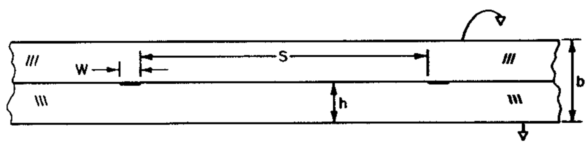

Fig. 1 Stripline geometry.

We procured 5-cm diameter, 125-µm-thick, c-axis-normal sapphire wafers. The constraint on the delay is determined by the thickness of the dielectric: the smaller the dielectric height, h, the narrower the linewidth, w, for fixed impedance and the more tightly spaced the lines, s, for fixed cross-talk. The dimensions of the 50Ω stripline delay line which had 25 ns delay and a design cross-talk (as predicted by backward wave coupling theory) of -53 dB were h=125 µm, w=42 µm and s=437 µm. The measured impulse response of this line is shown in Fig. 2. The amplitude reduction between the transmitted inpulse of Fig. 2(b) is attributed to the coax-to-stripline transition. In Fig. 2(c) the impulse response shows reflections as high as -24 dB. These reflections are apparently due to air gaps between the two sapphire dielectrics and preliminary indications of an improved packaging scheme suggest these can be reduced by another 20 dB. The cross-talk was below the noise in the measurement system (<-47 dB).

We also made a capacitively-coupled linear resonator by putting a small gap on each end of a 9-ns delay line made using the same stripline geometry. At 1.7 GHz the measured loaded Q of this resonator was greater than

10^5. The delay-line and resonator results demonstrate the feasibility of this new technology and verified our theoretical expectations for loss.

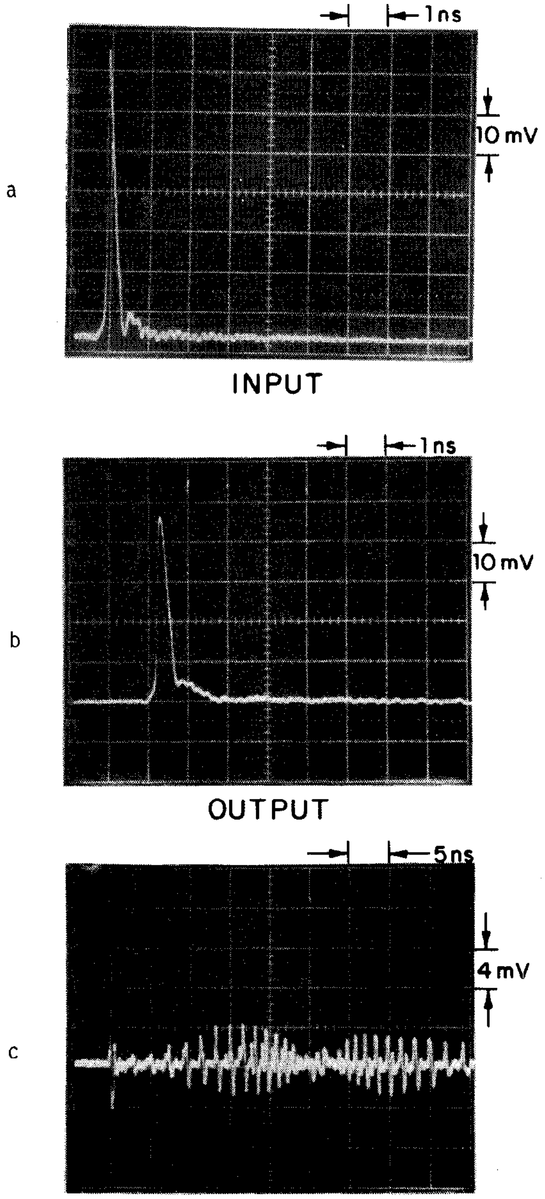

Fig. 2 Impulse response of 25-ns line: (a) input impulse, (b) transmitted output, and (c) reflected output.

We have designed and fabricated a linear-FM chirp filter and are currently testing it. The filter has 101 taps, a bandwidth of 2 GHz, a delay of 25 nsec and has a time-bandwidth product of 50. The double-spiral pattern of a tapped delay line is shown in Fig. 3. This geometry avoids tight-radius bends, allows arbitrary placement of taps, and permits the full utilization of round substrates. The proximity backward-wave coupler used with the double spiral is shown in Fig. 4(a). To realize a quadratic phase-vs-frequency characteristic which is required by the linear-FM chirp filter, the taps were spaced in delay so as to make the local resonant frequency a linear function of delay through the device. A complete mathematical design formalism has been adapted from that used in SAW chirp filters which employ a reflective grating to disperse the signal. These devices, called reflective-array compressors (RACs),[8] are mathematically and functionally similar to the tapped-delay-line structure but utilize different physical phenomena. The chirp spacing is shown schematically in Fig. 4(b). A photograph of the chirp filter just prior to final assembly is shown in Fig. 5.

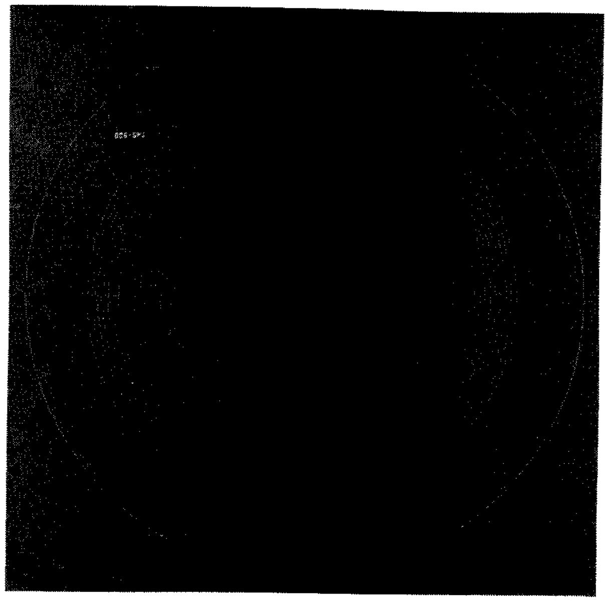

Fig. 3 Double Spiral delay line.

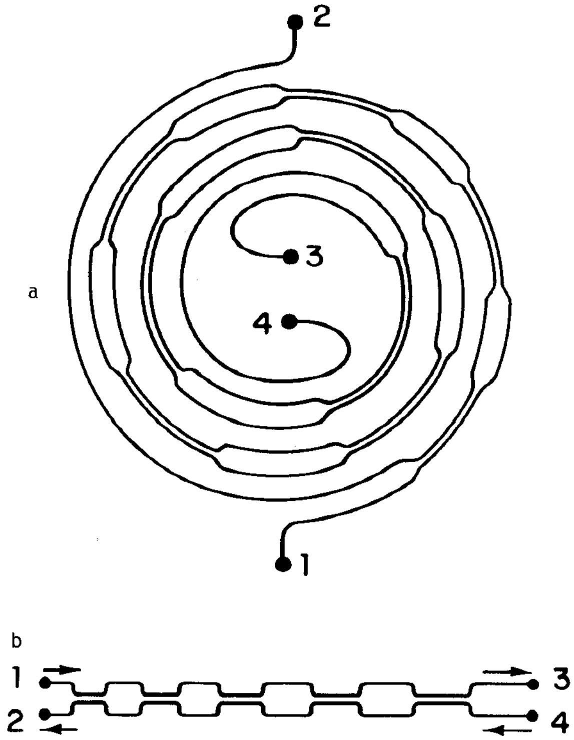

Fig. 4 (a) Double-spiral with proximity taps. (b) Schematic of Chirp tap spacing.

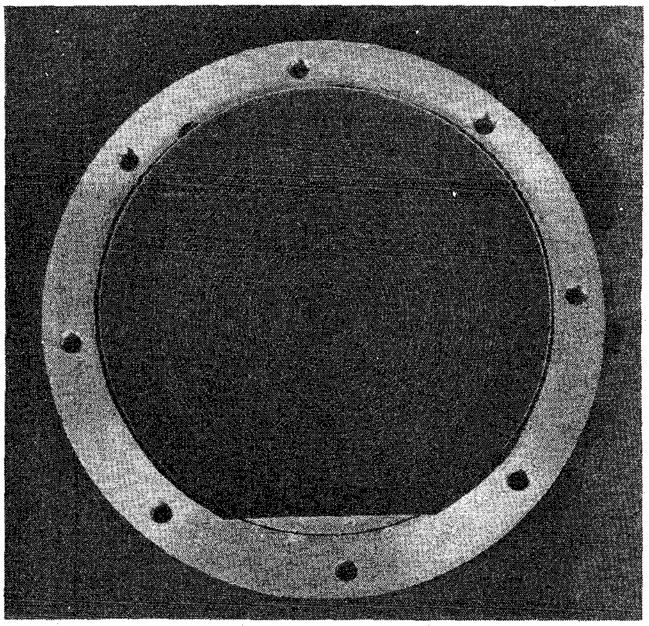

Fig. 5 Chirp filter just prior to assembly.

The step response of the chirp filter is shown in Fig. 6. These time-delay-reflectometry measurements show that the period at the beginning of the signal is about 200 psec (corresponding to 5-GHz instantaneous frequency) and at the end of the signal the period is about 330 psec (corresponding to 3-GHz instantaneous frequency). Although the output signal is only about 10 dB above the noise and contains spurious amplitude variations, the test result is a clear demonstration of the feasibility of the passive superconducting microwave circuit technology.

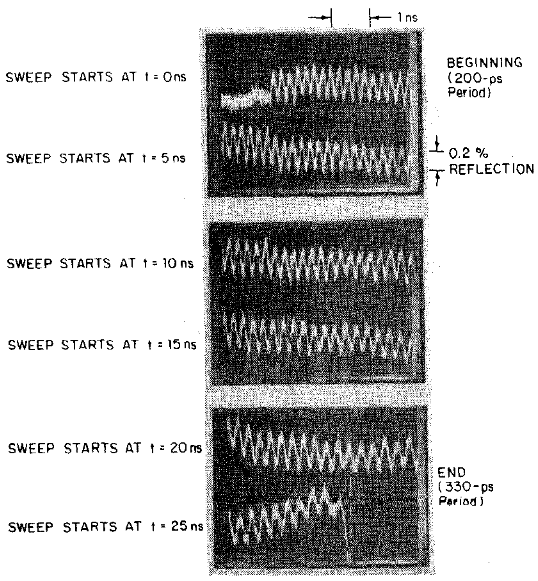

Fig. 6 5-3 GHz down-chirp step response.

Acknowledgements

The authors wish to acknowledge the support and advice of the following individuals: W. T. Brogan, S. S. Cupoli, G. L. Durant, W. Macropoulos, R. W. Mountain, R. W. Ralston, E. Stern and C. M. Vanaria.

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