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The discovery in 1987 of high temperature superconductivity (HTSC) in ceramic oxide compounds has given the Electronic Warfare and Microwave community another technology to help reach some of their most demanding goals.

The near term applications will be in passive microwave components, providing reduced insertion loss, smaller circuit and device size, and higher quality factor circuitry with less heat dissipation. Other applications are farther away and may not have even been conceived as of yet. All applications need to be assessed for their overall payoff compared to conventional technology to determine if the benefits of using superconductivity warrant cryogenic cooling.

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High Temperature Superconductivity Applications for Electronic Warfare and Microwave Systems

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The discovery in 1987 of high temperature superconductivity (HTSC) in ceramic oxide compounds has given the Electronic Warfare (EW) community another technology to help reach some of its most demanding goals. Future EW systems will require more capabilities in smaller packages. Increased sensitivity, more sophisticated signal processing, faster and more accurate emitter detection and tracking are a few of the most demanding needs which advanced technologies will have to address. Surely, HTSC will not solve all of these future EW needs but it will definitely have a major impact in certain areas.

SUPERCONDUCTIVITY TUTORIAL

Superconductivity is the physical phenomenon which allows the flow of direct current (DC) without resistive loss. Resistance to the flow of alternating current (AC) is extremely low compared to normal metals but is not exactly zero due to kinetic inductance (the interaction between lossless superconductive electron fields and ohmic normal electrons causing resistance). Microwave surface resistances (Rs) more than four orders of magnitude lower than copper have been demonstrated **(1)**. From 1911 to 1986, superconductivity was only attainable in metallic low temperature superconductors (LTSC) at temperatures below 30 Kelvin (-406 F) which made superconductivity impractical for most applications. By mid 1987, HTSC had been discovered in a ceramic Yttrium compound with a transition temperature (Tc) above 90 Kelvin (-298 F). By the end of 1988, superconductivity had been observed in Bismuth and Thallium ceramic compounds at temperatures of 110 Kelvin (-262 F) and 125 Kelvin (-235 F), respectively **(Fig. 1)**. Just recently, an announcement by Wayne State of superconductivity as high as 265 Kelvin (17.33 F) is believed to be true but still awaits confirmation by other labs (2). The significance of these higher Tc superconductors is that they can be operated with smaller, lower power and more reliable coolers. It is even conceivable to use liquid nitrogen (77 Kelvin, -321 F) cooling. There have been many new compounds discovered since these main three HTSC compounds, but the first generation of systems using HTSC will surely be limited to the Yttrium, Bismuth and Thallium compounds.

Although it is true that all three compounds have Tc's well above liquid nitrogen temperature, the highest allowable operating temperature depends on the application. For most applications HTSCs will be operated between .5 to .8 of their Tc value to ensure good performance. For less demanding low power applications the operating temperature will be higher than for more demanding higher power applications (3). For the Yttrium compound, the operating temperature will most likely lie between 45 and 75 Kelvin while Thallium could operate between 60 and 100 Kelvin. Device operating temperatures must be considered at all points of the development cycle in order to ensure that the system is practical or could easily become practical for a given application.

Many applications for HTSC will simply be scaled-up versions of LTSC applications but at a much more manageable temperature. The most exciting uses, however, will be new and novel applications that exploit the unique properties of these HTSC ceramic oxide materials, which are much different from their more mature metallic LTSC counterparts. For example, HTSC materials have high resistance in the normal (non-superconducting) state and very low loss in the superconducting state, and appear to possess extreme radiation hardness (4). A number of HTSC applications have already been identified as providing certain payoff for EW systems, especially in systems where performance is the primary or sole concern and cryogenic cooling can be tolerated. In trying to determine potentially worthwhile applications, only those that meet the following criteria have the greatest chance of finding their place in EW and defense systems: 1) those providing at least an order of magnitude of improvement over competing technology (performance, size, weight, power, or cost) or 2) applications that are only possible with superconductivity. If these criteria are not met, there may not be enough incentive to design/redesign a system using superconductivity instead of conventional technology. All applications need to be assessed from an entire system viewpoint to determine if the system improvement warrants cryogenic cooling.

There is no argument that the first EW applications of HTSC will be in passive microwave components because their implementation depends basically on depositing and patterning high quality thin films on low microwave loss substrates. Performance advantages for these devices have already been demonstrated in the more mature low temperature superconductors, taking advantage of the low microwave Rs superconductivity provides. This low resistance allows reduced insertion loss, smaller circuit and device size, less system weight, power and heat; as well as, higher quality factor (Q) circuitry. For micro and millimeter waves, using superconducting stripline or microstrip technology gives the low loss performance of waveguide but at a much smaller size, weight and cost. Losses in normal metals increase by the square root of frequency. Losses are so bad with conventional copper at millimeter wave frequencies that waveguide technology must be used exclusively in certain applications, but superconductivity enables the use of stripline and microstrip technology with the same performance as waveguide implementations.

Presently, HTSC materials are not optimized to their full potential. The best superconductive films at liquid nitrogen temperature have Rs's 100 (10 GHz) to 1000 (2 GHz) times less than copper at the same temperature. Currently, HTSC materials show enormous potential for making devices that will perform better than conventional technology below 20 GHz **(Fig. 2)**. In the next two years, Rs's will drop another one to two orders of magnitude for all frequencies as fabrication technology improves the quality of the HTSC films. In order for HTSC to impact millimeter wave systems as LTSC has, these material advances will be required **(5)**.

NEAR TERM APPLICATIONS

With current or near term (1-2 years) fabrication technology, it is possible to develop the following HTSC components:

1) MMIC Filters
2) MMIC Delay Lines/Phase Shifters
3) Microwave Resonators
4) Antenna Feed Networks
5) Low Frequency Antennas

1) Current microwave filters possess larger insertion loss and size than is desirable for future EW systems. In some instances receiving systems use down conversion to an IF band before filtering, but system size, sensitivity and

dynamic range are sacrificed in the process **(6)**. Superconductivity allows Monolithic Microwave Integrated Circuit (MMIC) filters to be implemented (small and light weight) with the same or better performance as much larger and heavier conventional technology filters **(Fig. 3)**. Superconductivity makes it practical to achieve low loss, low noise, narrowband (high Q) filtering directly at microwave frequencies (without requiring down conversion) for greater sensitivity, dynamic range and reduced system size and weight. A 1 x 1 cm, four-element HTSC filter achieving less than 0.05 dB insertion loss across a 10 percent bandwidth at 10 Ghz has already been demonstrated **(7)**.

2) Microwave delay lines have various applications in EW and microwave systems both in the dispersive or non-dispersive form. HTSC delay lines for instantaneous frequency measurement (IFM), as well as, switched delay lines for EW radar range deception and low loss, high resolution MMIC phase shifters can and are being built. For example, a 14-cm long delay line on a 1 x 1 cm substrate has been fabricated, producing a one nanosecond (nsec) delay at 461 Mhz while showing only a 0.005 dB insertion loss --- 2000 X less loss than much larger surface acoustic-wave (SAW) or bulk acoustic-wave (BAW) devices performing similar delays **(7)**. Compared to conventional delay line technologies, superconductivity makes smaller, higher frequency, wider bandwidth and lower loss delay lines possible.

HTSC dispersive (Chirp) delay lines will give wide-band frequency compression for EW compressive/microscan receivers and wide-band EW spectrum analyzers. An LTSC dispersive delay line has been built by MIT Lincoln Lab with a bandwidth of 2.6 GHz and a designed insertion loss of 5 dB **(8)**. It is projected from current RF loss measurements that a compact HTSC dispersive delay line with a delay of 100 nsec and an insertion loss of only 2.3 db could be built (9).

A number of applications using superconductive delay lines to achieve low loss, high resolution MMIC phase shifters can be envisioned. One use would be in a polarization control network (PCN) for active solid-state array transmitters (Fig. 4) (10). Polarization ECM will most likely be a technique used in advanced ECM systems and requires precise polarization control of the transmitted signal. Currently, vector modulators use ferrite phase shifters to achieve low loss and wide bandwidth, but due to their large size they must be placed before the power distribution network of the array (Fig. 5). It would be desirable to implement a vector modulator in MMIC technology and integrate it with a 2-3 watt MMIC amplifier in each antenna element. This would eliminate half the required feed network and active amplifiers from the system. The phase tracking between the two orthogonal outputs of each element would also improve because both would be driven by a common amplifier. But this is impractical to implement with conventional MMIC because GaAs device losses could be on the order of 15 dB/phase shifter in a high resolution device. To achieve a desired effective radiated power (ERP) from the array, vector modulator losses would have to be compensated by larger amplifiers, adding size and increased power requirements to the system. This added power would exceed GaAs MMIC's capability. If HTSC devices could be fabricated with losses well under 1 dB (conductor, switching and dielectric loss) and made capable of handling sufficient power (2-3 watts), it would allow a reduction in the required input RF power to the vector modulator while maintaining small size, high reliability and achieving improved performance.

3) High Q resonators for stabilizing low-phase noise oscillators in both cavity and stripline configurations have been demonstrated in niobium at liquid helium temperatures --- showing substantial phase noise improvements over SAW and Quartz oscillators **(Fig. 6)**. Reductions of 10-30 dB in frequency instability can have significant effects on system and mission performance. A 77 Kelvin, 10 Ghz HTSC microstrip resonator has been fabricated with a Q 10 times that of a cooled copper resonator **(7)**. An initial application for EW would use a HTSC resonator to stabilize a frequency synthesizer or system local oscillator (LO). As threat radar systems become more coherent in their operation, the ECM systems used to counter those radars must have at least equal coherency to accurately detect a threat signal and create a credible false signal for transmission. The receiver and signal generator stability could become a major factor in producing credible waveforms for use in jamming or deception. A second application of a HTSC resonator is in Doppler radar systems for picking out low radar-cross-section (RCS) targets in a high clutter environment. This detection ability is a function of the LO stability and a reduction of 10-30 dB in phase noise would make a major impact on the probability of detecting low RCS targets **(8)**.

4) HTSC will also allow low loss antenna feed networks for micro and millimeter wave frequencies. Superconductivity permits extremely low loss, low dispersion, microwave transmission lines to be implemented, which have been shown to preserve pulse widths and amplitudes over much greater distances and higher frequencies than conventional copper transmission lines **(11)**. Much larger arrays can be made practical with loss performances equivalent to much smaller arrays.

5) The benefit of using superconductivity for reduced size and increased gain of electrically small, low frequency antennas has been demonstrated in both low and high temperature superconductors. A one-cm^2, 400 MHz loop antenna was fabricated in LTSC with a gain comparable to a 30-cm^2 non-superconducting antenna **(12)**. In 1988, ICI Composites Inc. made a 2.6" HTSC antenna. While operating at 550 MHz and 77 Kelvin, it showed a gain 6 dB greater than a copper antenna cooled to 77 Kelvin **(13)**.

FAR TERM APPLICATIONS

Future HTSC applications will require further development in fabrication and material technologies.

Superconducting magnets will impact electron beam focusing in EW Traveling Wave Tubes (TWTs) by generating much greater fields than conventional focusing technology. HTSC magnets will also enable compact high power microwave generators and energy storage. In space, where size, reliability and power are major concerns, HTSC will allow smaller, higher power generators which require much less cooling than LTSC or copper generators **(14)**.

Other far term potential areas of applications for HTSC will require the development of a two terminal switching/detection device known as a Josephson Junction (JJ). This device has been demonstrated in LTSC and is used in very stable (low noise), frequency selective, oscillators and very low noise, fast responding micro/millimeter wave/IR detectors and mixers. A JJ is also used as a digital device and has been demonstrated to switch near a picosecond (ten times faster than the fastest semiconductor switch) while using 3 orders of

magnitude less power than conventional semiconductor devices **(Fig. 7)**. In 1987, Fujitsu demonstrated a 4-bit microprocessor in LTSC which performed nearly 16 times faster (1.1 GHz) than an actual GaAs circuit (70 MHz) designed in 1986. Just recently, MITI (Japan) announced the completion of an entire low temperature superconducting computer consisting of 4 superconducting chips. The computer processes most instructions in 1 nanosecond, ten times faster than the fastest silicon-based processors and several times faster than GaAs based CPUs. What is even more amazing is the fact that the unit only consumes 6.2 milliwatts of device power **(15)**. The drawback is that liquid Helium cooling is large, complex and expensive. Even with this limitation, future EW processing speed requirements may demand the use of LTSC digital electronics because its high speed and low power characteristics allow faster, higher density processing not possible with semiconductor technology. When HTSC materials become practical, it is very possible we will see EW processors incorporating HTSC to meet future processing requirements. An interesting concept is making semiconductor/photonic/HTSC hybrid circuits and devices operating at an optimum cryogenic temperature (possibly liquid nitrogen temperature or higher) and combining the performance advantages of each technology on the same chip. Another novel idea is using superconductive interconnects between chips and circuit boards **(16)**.

In summary, many experts believe that the impact of HTSC will equal or exceed that of the transistor or laser. Probably the most significant applications have yet to be envisioned, but it is certain that EW and microwave systems will benefit from HTSC near term in the area of passive microwave components and circuitry. Future HTSC system applications are also certain to evolve and will need to be assessed for their overall system payoff compared to conventional technology.

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TIME LINE FOR DISCOVERY OF SUPERCONDUCTORS

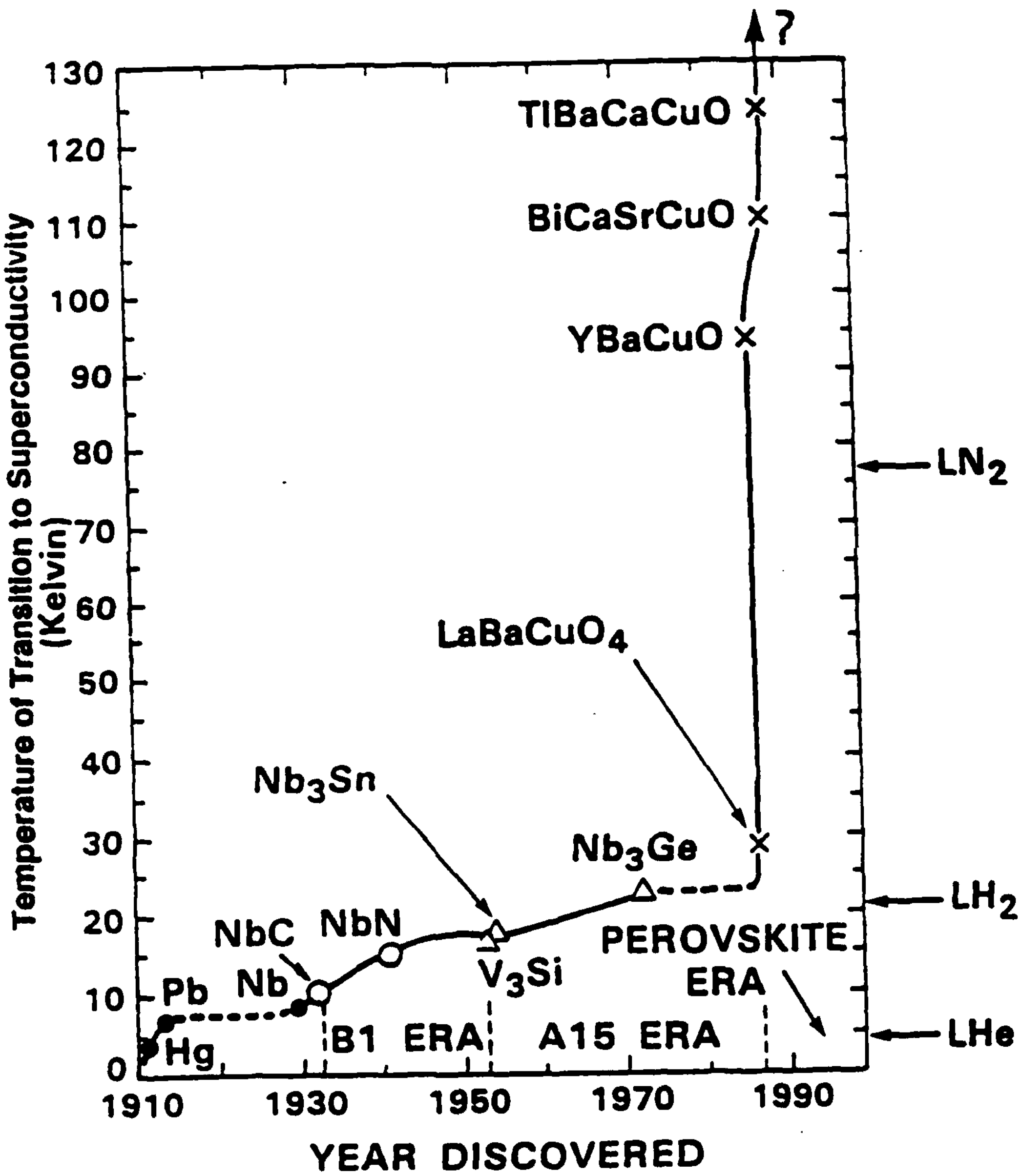


Fig. 1

Surface Resistance of High-T_c Superconductors

YBaCuO Ceramics

- ▾ Argonne, 77K
- ▫ Cornell, 4K
- ▵ Rutgers/Sarnoff, 10K
- ✪ Northeastern Cavity, 4K

YBaCuO Crystals

- + AT&T/Cornell, 77K
- ✧ AT&T/Cornell, 4k

YBaCuO Thin Films

- • Bellcore/Sarnoff, 79K patterned
- ▾ Bellcore/UCLA, 77K
- ◆ Siemens, 77K patterned
- ▴ NASA 77K patterned
- * Siemens/Wuppertal, 77K
- ✱ TRW, 60K
- ○ Bellcore/Sarnoff, 5K patterned
- ▿ Hughes/Lincoln Lab, 4K
- ▿ AT&T/Lincoln Lab, 4K

TlBaCaCuO Thin Film

- ■ STI, 77K patterned

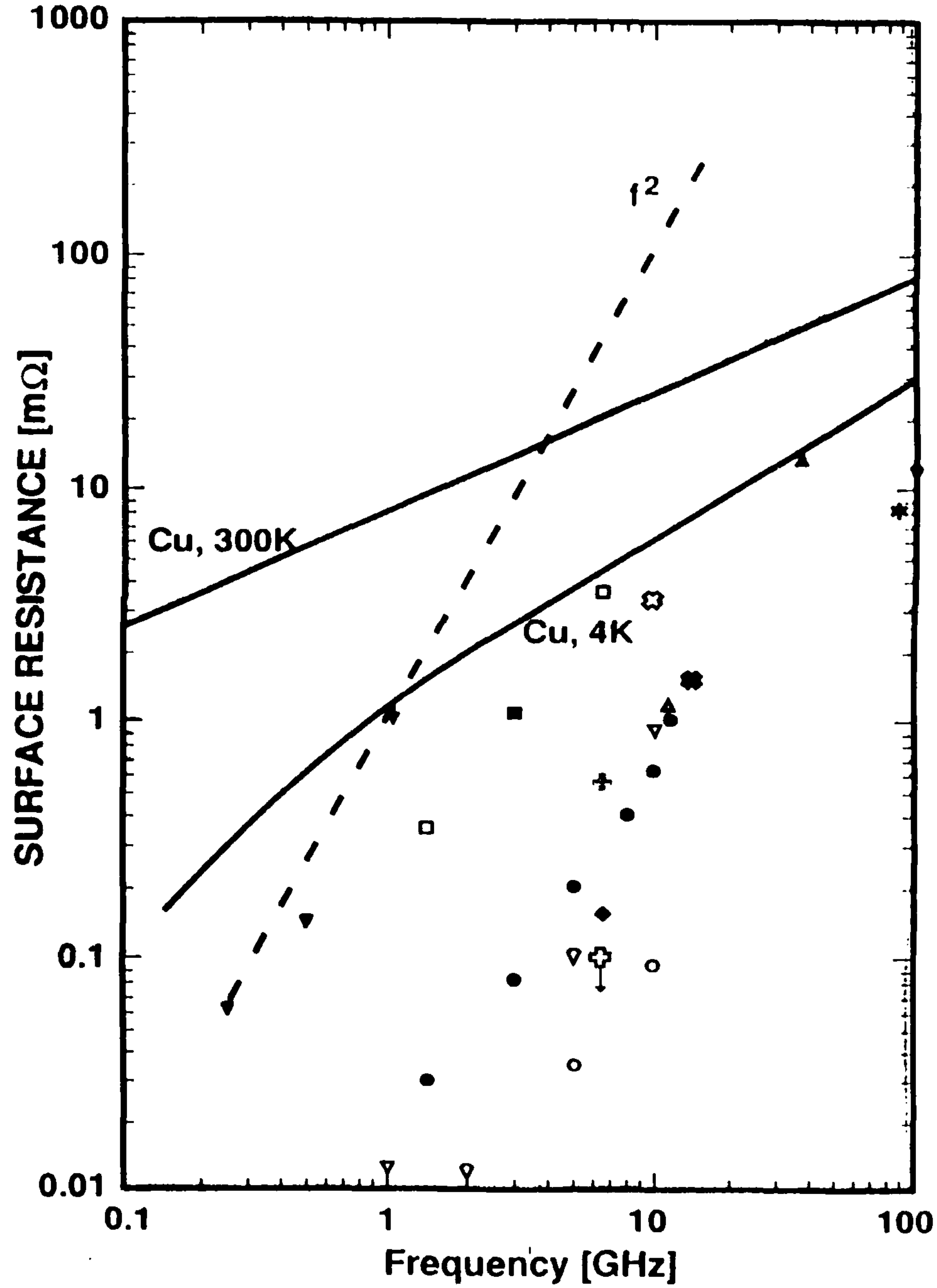
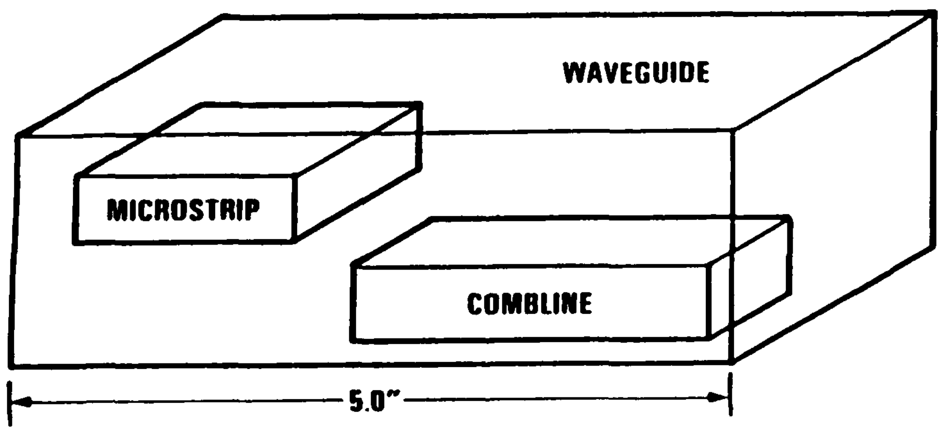


Fig. 2

Comparison of Filter Technologies

5-pole Chevyshev Filter with 0.01 dB Ripple at 10 GHz with a 1% Bandwidth

Filter	Insertion Loss*	
Waveguide	0.75 dB	1.19
HTS Microstrip	1.80 dB	1.51
Combline	3.25 dB	2.11
Cu Microstrip	10.00 dB	10.00



*Assumes R_S (HTS) = R_S (Cu)/10   Data provided by the TRW Antenna Lab

Fig. 3

SUPERCONDUCTIVE PCN

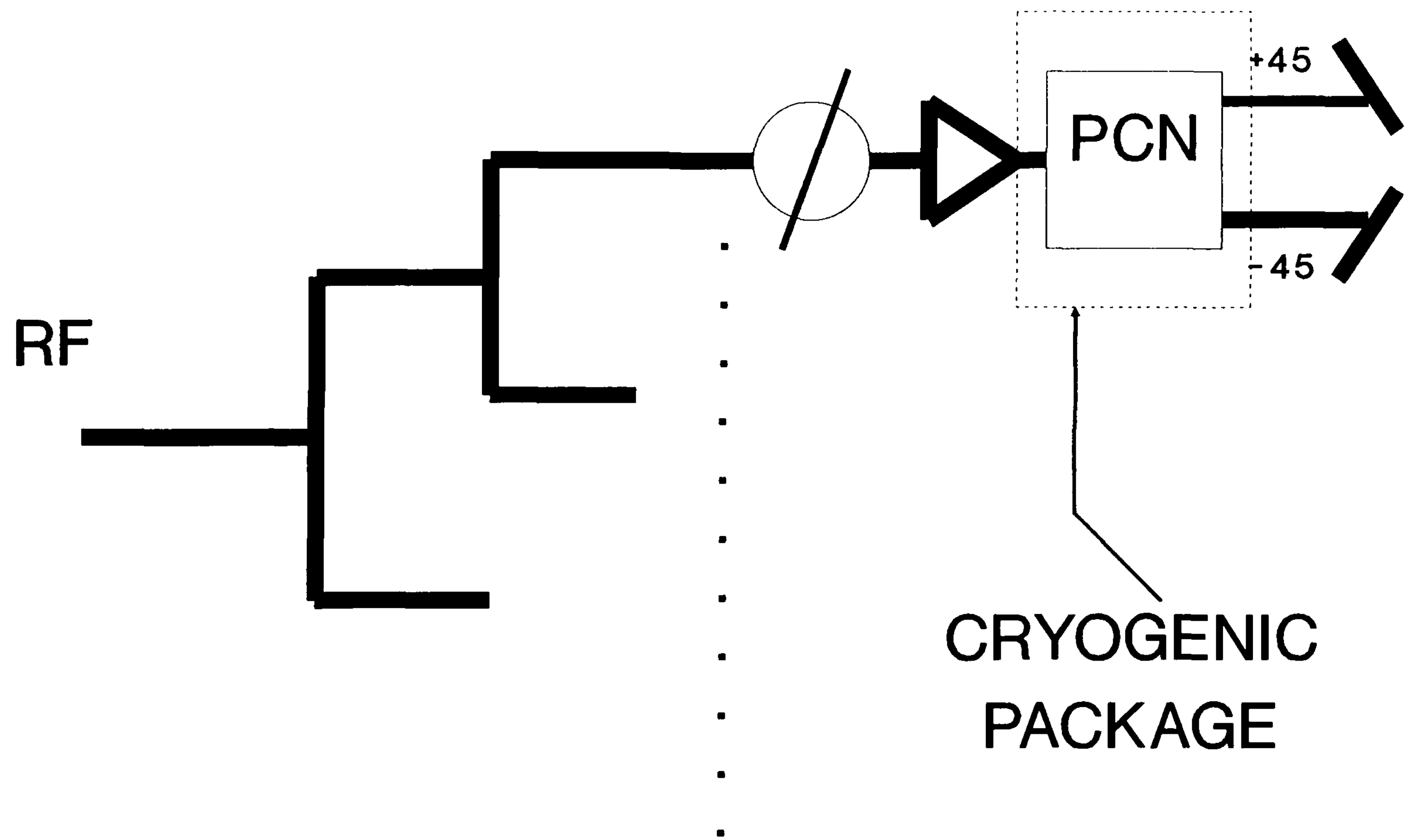


Fig. 4

PRESENT PCN

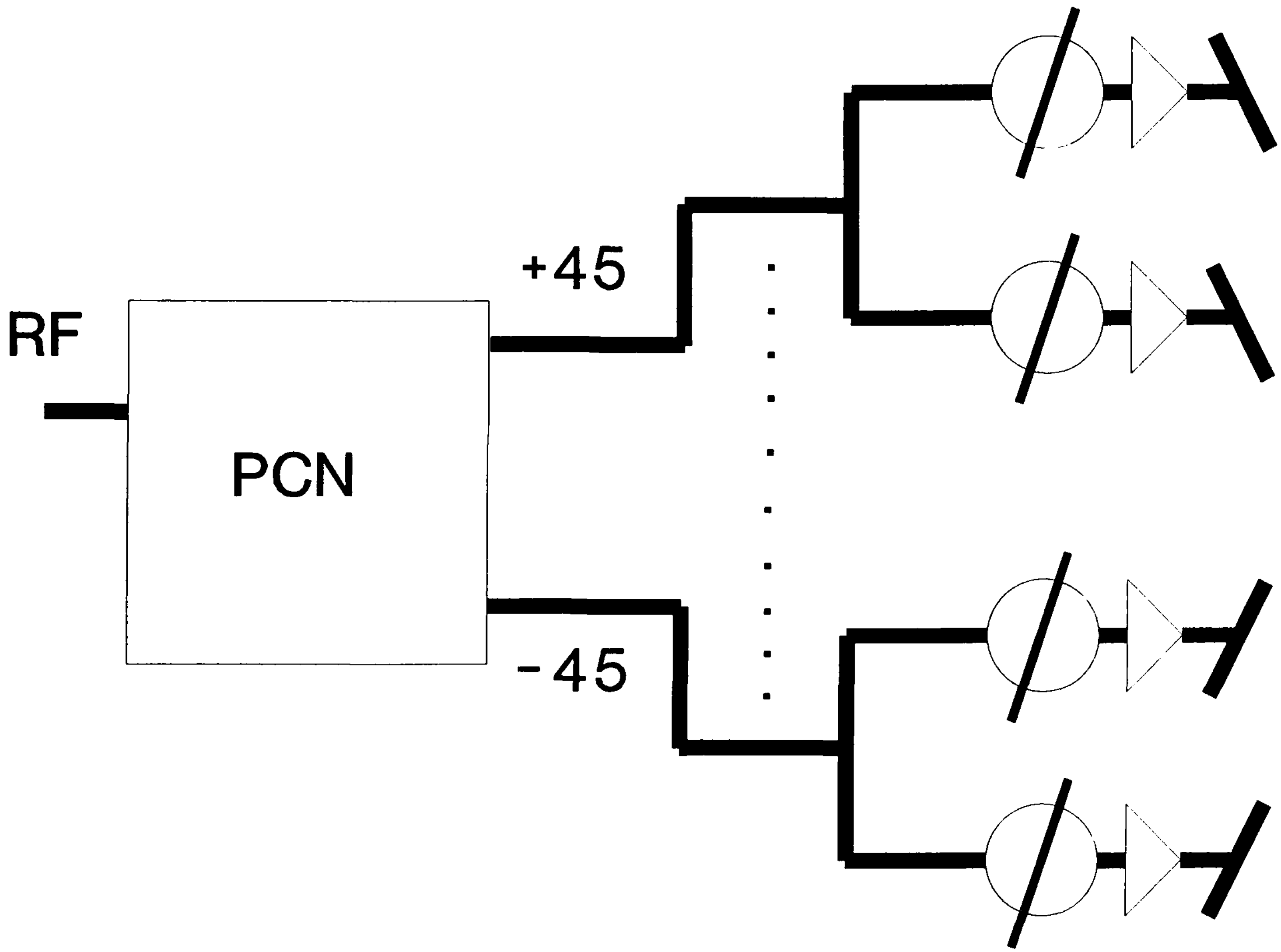


Fig. 5

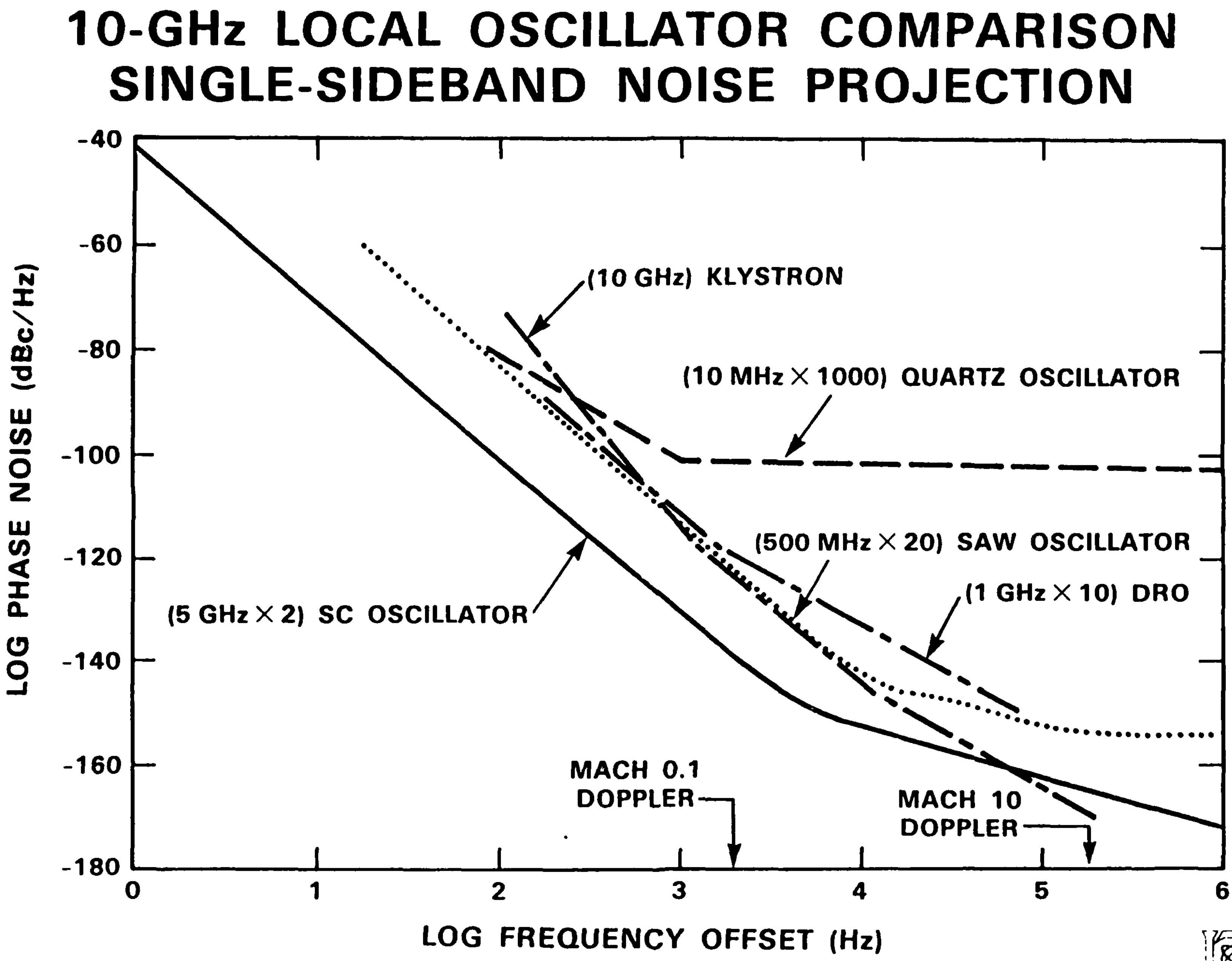


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Fig. 6

DIGITAL SUPERCONDUCTING/SEMICONDUCTING GATE/CIRCUIT COMPARISONS

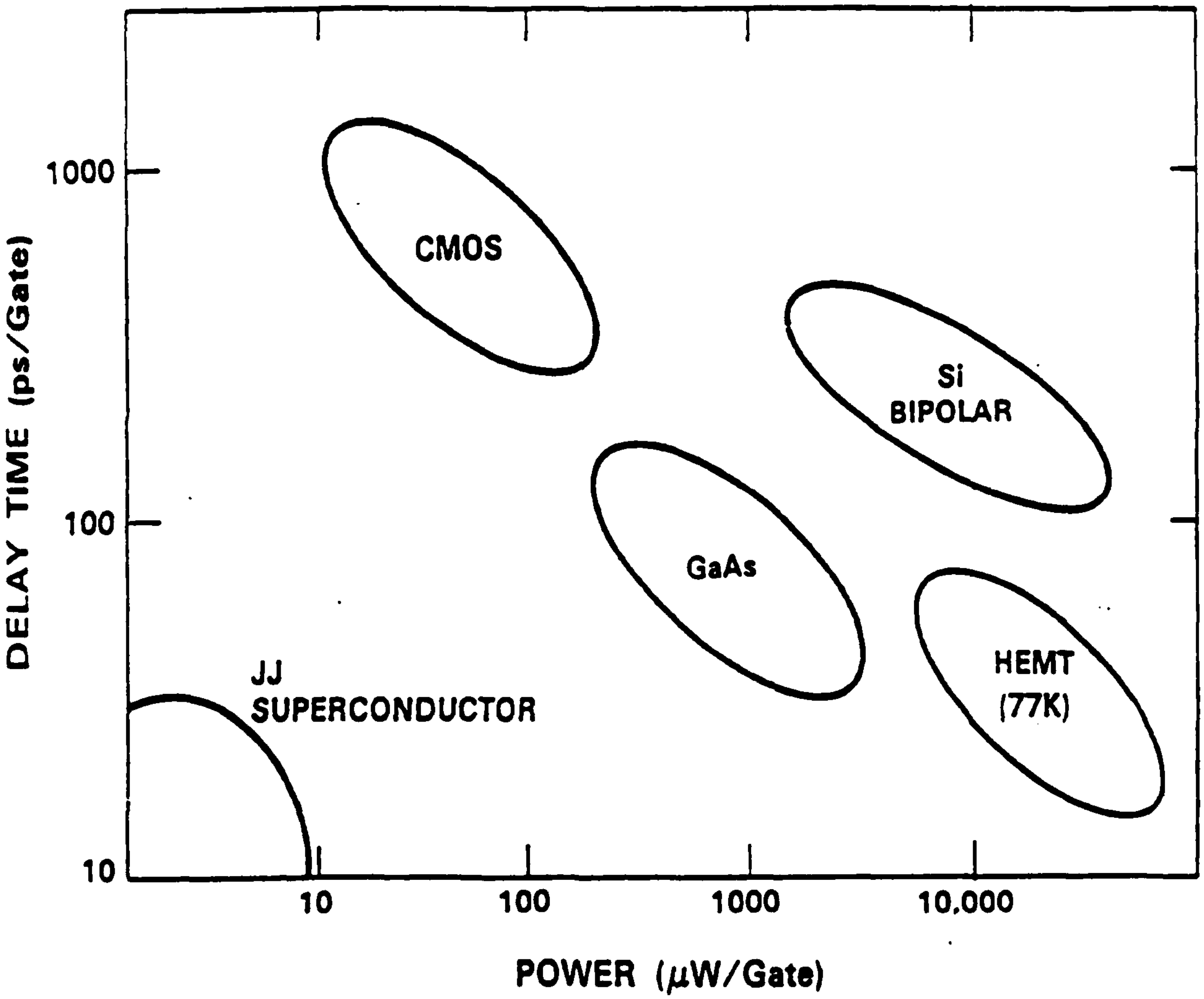

Fig. 7