Potential Microwave Applications Of High Temperature Superconductors

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Abstract :

The present paper describes the startling discovery of superconductors with transition temperatures about 90^0 K which is above the 77° K temperature of liquid nitrogen, has created great interest Superconductors can produce microwave circuits with lower conductor loss, lower noise and wider bandwidths. Some examples are given along with the status of the first microwave measurements.

Index Terms :

Superconductors, Bandwidth, Microwave

I. INTRODUCTION

The startling discovery of super- conductors with transition temperatures in the 90°K range has created great Interest. President Reagan, who spoke at the Federal Conference on the Commercial Applications of Superconductivity on July 28, 1987, announced a new DoD initiative on high temperature superconductivity of $150 M over a three-year period. He also proposed doubling the NSF budget in the next five years. Paul Chu, who leads the University of Houston group that first published on the yttrium-barium-copper oxide ceramic having a 93°K transition temperature, was supported by the NSF. Chu and his co-workers' paper[1] was received by Physical Review Letters on February 6, 1987, only weeks ahead of the Japanese Journal of Applied Physics paper on the same subject[2] President Reagan closed his keynote address by saying that our economy is not so much natural resource-limited as information-limited: "We live in an age of mind over matter. A new premium is placed on the human heart and mind."

The federal conference was sponsored by the Executive Office of the President, the Office of Science and Technology Policy and the Departments of Energy, Commerce and Defense. In chairing the opening session, William R. Graham, science advisor to the President, noted the 3000-fold cost advantage of refrigerating with liquid nitrogen at 77°K compared to the cost of refrigerating with liquid helium at 4.2°K. Before the discovery of the 90°K superconductors, refrigeration at 4.2°K was required. In his remarks at the close of the meeting, Graham said "We have won in the research tab. We now need to win in the marketplace. This summarized the major concern in Washington that the US, not Japan, win the race for the commercialization of superconducting products.

The motivation for comniercializing a product ultimately is the market, which is critically dependent on the importance of the application. We shall first discuss present applications of liquid helium refrigerated superconductors. These applications should be more

pervasive with liquid nitrogen refrigerated superconductors. In addition, new applications inherent in the unique properties of the ceramic yttrium-barium-copper oxide superconductors may emerge.

The first applications of the new superconductors may be in electronics already operating at 77°K, such as supercomputers operating at this temperature to enhance the speed of silicon CMOS. The temperature on the shadow side of a satellite In space can be below 90^0K.

The advantages of superconductors may be summarized as lower conductor loss resulting in lower noise, higher speed and wider bandwidth.

Lower Loss

Microwave circuits using niobium superconductors refrigerated with liquid helium are being used today to achieve lower conductor loss. These include niobium strip- line circuits and cavities. The strip- line circuits deposited on silicon substrates are used as gigahertz bandwidth pulse expanders arid compressors.[3] Microwave cavities are used in accelerating charged particles for high energy physics “super-colliders.” Congress appropriated funds for the next generation. “super-collide?’ before the discovery of the 90° superconductor. Physicists presently are debating whether to delay Construction Until the “90 K technology” becomes available for use. Cavities also are used for very stable low noise oscillators in frequency control. These applications could be extended to banks of more selective filters for increased communication channel capacity.

The 90°K superconductor has the potential to substantially Improve the performance of monolithic microwave Integrated circuits. The lower circuit loss leads to higher Q lumped circuit elements and transmission lines. Lower circuit loss results in less amplifier gain required to restore the loss. Most importantly, solid-state transistors work much better at temperatures in the 77^0K range. Semiconductor motilities increase and resistive losses decrease, resulting in transistors with higher gain and lower noise. Aging effects are slower at low temperatures, resulting in higher reliability. The ultimate result will be monolithic microwave Circuits with higher performance and lower cost.

Substantial advances In fabricating the 90’K superconductors will be required to make their processing compatible with monolithic microwave integrated circuits. At present, the final step in processing yttrium-barium-copper oxide thin films is a 900°C anneal in oxygen. The 900°C temperature will destroy circuits already fabricated on silicon or gallium arsenide. One solution would be to fabricate the superconductor first It may be possible to develop superconductor fabrication processes that do not require the high temperature anneal.

Low loss is of course most critical at high power. A 3 dB loss for an incident power of 1 kW results in the dissipation of 500 W, while a 3 dB loss at lower incident powers is proportionally lower. The present goal of material research is to increase the power density limits of superconducting materials. Such materials could then be used in components such as high power phase shifters in phased array antennas, power combiners and high power tubes. Tubes also could benefit from the higher magnetic fields expected from high temperature superconductors.

Lower Noise

The lowest noise mixers available today are made with a superconductor-Insulator-superconductor diode. Noise figures of. about 1 dB (noise temperatures of 55 to 65° K) in the 50 to 110 GHz range have been achieved[4] with Pb(lnAu) ox- ide-Pb(Bi) tunnel junctions. Noise figures of room temperature Schottky barrier diodes are about 5dB up to l00GHz.

The lower noise figures will –have a substantial impact on communications systems. One payoff of a 4dB decrease in noise figure is to reduce the area of the receiving antenna by a proportional 4dB. Since the cost of an antenna Is generally proportional to Its area, a substantial cost savings can be realized. The savings for a millimeter phased array receiving antenna can be on the order of $1 M. If the antenna is kept the same size, then the communications system will have longer range. Another option would be to decrease the transmitter power.

Higher Speed and Wider Bandwidth

The higher speeds and wider bandwidths achievable with super- conductors have important implications for instruments, computers and systems. An important example is the picosecond signal processor recently marketed by Hypres. This instrument can operate as a digital sampling oscilloscope having an internal rise time of 5 ps, a sensitivity of 50μV and a bandwidth of 70 GHz. Only the Josephson junctions on the "front end" need to be cooled. This is done efficiently by spraying the niobium circuit chip with liquid helium. This Instrument for microwave/mm-wave circuit measurements has the shortest rise time and widest bandwidth.

Present supercomputers such as the Cray are capable of about a billion operations per second and require a substantial cooling system. High temperature superconductors have the potential of increasing this capability to a trillion operations per second. Such speeds already are achievable with specialized analog processors.[3]

Superconducting technology should make possible radar and communications systems operating in the 100 to 1000 GHz range. These systems are suited uniquely for applications in space. RADC had programs under way to develop superconducting niobium nitride before the discovery of the 90K ceramic, which will make these systems easier to refrigerate.

Microwave Experiments

The resistance R of superconductor at microwave frequencies is not zero, as it is for DC, but is equal to where R(res) is a temperature-dependent residual resistance close to absolute zero and R(T) temperature - dependent resistance.[5] The Bardeen, Cooper, Schrieffer theory of superconductivity predicts that

$$R(T)\text{- const} \times f^{\alpha} \times e^{\Delta/kT}$$

where f is the frequency, Δ is the superconducting energy gap, a Is generally 1 to 2, k is Boltzman's constant and T is the temperature. For a well-developed superconductor like niobium, R(T) at 4.2^0 K is about three orders of magnitude lower than that of room temperature copper at 100 GHz and about two orders of magnitude lower at 100 GHz. The liquid helium temperature of 4.2^0 K is about one half of niobium's superconducting transition temperature. This is in agreement with the "rule of thumb" that super- conductors should be operated at about one-half their transition temperature. Yttrium-barium-copper oxide therefore should be used at 45^0K. The 77°K temperature of liquid nitrogen can be lowered with a vacuum pump. Liquid neon can serve as a 28°K refrigerant

Sridhar, Schiffman and- Hamdeh have published the first measurement of the surface resistance of ceramic yttrium-barium-copper oxide at 9.85 GHz in the August 1987 issue of the Physical Review B[6] The temperature dependence of the resistance from 70 to 90°K is reasonably well described by the Bardeen, Cooper and Schrieffer (BCS) theory of superconductivity in the very "dirty" (mean free path of electrons about 10 A) limit Below 70°K, agree- ment with the BCS theory was poor.[7] The magnitude of the resistance was equal to that of copper at 70% and the residual resistance at very tow temperatures was about one-tenth that of copper.[7] This relatively high superconducting resistance may be due to granularity and anisotropy of the "dirty" ceramic material. We hope that lower resistance will be observed for the thin-film measurements under way at RADC and other laboratories. Crltical DC current measurements on thin films made at Stanford University[8] and at IBM[9,10] at were orders of magnitude better than for the Ceramics. These thin films were much closer to ideal single crystals than were the ceramics.

Conclusion

High temperature superconductors have the potential for many important microwave/mm-wave systems applications. A sustained research and development effort will be required for these new super-conductors to reach their potential. A fundamental theory that explains why these new materials superconduct is needed, together with improved materials fabrication and testing. In the future the resistance anomalies observed above 90^0K may lead to room-temperature superconductors.

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