Selected Technology Summaries for Microwave Theory and Techniques—1988

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Abstract—**This paper includes a summary of the technical advances during the years 1984–1988 in nine technical areas of interest to the microwave community. These areas are computer-aided design; acoustics; lightwaves; integrated circuits; network theory; packaging; ferrites; systems; and superconductivity.**

Introduction

THIS PAPER is a continuation of the technology summary articles started in 1954 and consists of summaries of the state of the art and technical advances for the years 1984–1988 in selected areas of interest to the IEEE MTT-S members [1], [2]. The contributions included here were prepared by the technical committees of the IEEE MTT-S Administrative Committee (AdCom). These are standing committees of technical experts in selected disciplines germaine to the MTT-S membership interests.

The principal contributors to each summary are identified along with the technical committee involved. Each summary contains a brief overview of the technical area, so that the reader may 1) gain an update on the state of the art in this particular area and 2) have a technical overview and references to begin a more comprehensive study.

The 1988 summaries were provided by the following technical committees:

- MTT-1 Computer-Aided Design (B. S. Perlman, Chairman)
- MTT-2 Microwave Acoustics (T. J. Lukaszek, Chairman)
- MTT-3 Lightwave Technology (C. Lee, Chairman)
- MTT-6 Microwave and Millimeter-Wave Integrated Circuits (J. C. Wiltse, Chairman)
- MTT-8 Microwave Network Theory (P. LaTourrete, Chairman)
- MTT-12 Microwave and Millimeter-Wave Packaging (B. Berson, D. Maki and F. J. Rosenbaum, Cochairmen)
- MTT-13 Microwave Ferrites (W. E. Hord and J. M. Owens, Cochairmen)
- MTT-16 Microwave Systems (G. L. Heiter and J. B. Horton, Cochairmen)
- MTT-18 Microwave Superconductivity (E. F. Belohoubek, Chairman)

Manuscript received February 1, 1989.
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The contributions of the technical committees are greatly appreciated. Special thanks go to the authors of the summaries.

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Trends in Microwave Design Automation

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COMMITTEE MTT-1

Electronic design automation is having a great impact on microwave circuit design. The trend in microwave design is to improve cost, reliability, and performance by taking advantage of advances in computing technology, advanced modeling and simulation techniques, and features similar to those typically associated with digital computer-aided design (CAD). Improved design automation for microwave circuits is needed to support increased circuit complexity and level of integration. In particular, the rapidly growing field of monolithic microwave integrated circuits (MMIC's) has had considerable impact in spurring physics-related simulation and design concepts. This is reflected in the recent special issue of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES on CAD (vol. 36, no. 2, Feb. 1988). Two overviews on electromagnetic and nonlinear CAD describe the status of computer-aided design as of 1987 [1], [2]. The following paragraphs summarize the main trends of CAD as of mid-1988.

In order to make microwave circuit analysis and optimization more efficient, some researchers have started looking into applications of now easily accessible vector processors such as the Cyber 205 or Cray X-MP [3], [4].

The key advantage of using these machines is that similarly structured computational steps in analysis and optimization algorithms can be carried out in parallel (in the pipeline sense) by the specialized vector hardware. Such algorithms appear to be very well suited for microwave CAD for the following two reasons. First, typical microwave circuits contain only a few types of components, repeating themselves with slightly different parameters in different parts of the circuit. Second, in most of the microwave circuits it is required that the analysis be carried out at a large number of frequency points. When a vector processor is being used for the analysis of such a circuit, all these microstrip sections may be combined into single multidimensional "supercomponents." This supercomponent concept has been discussed in [1] and it has been pointed out that vectorization of algorithms provides a more efficient use of computer time and is less costly.

New techniques are being applied to circuit simulation. Simulators and analysis tools using numerical approaches with formulations in the space domain [5] and in the spectral domain [1], [6], [7] are becoming available. These can be divided into two groups. One addresses the numerical analysis of geometrically complex HMIC and MMIC passive circuit geometries [1], [5], [7]; the other [6] stresses the strictly rigorous and accurate full-wave characterization of regular and irregular, relatively basic shapes such as single and multiple interacting discontinuities. With the field-theory-based lookup table concepts applied in [1], interactive CAD is possible. With rapidly accelerated algorithms such as the spectral operator expansion technique (see [1, ref. 22]), real-time numerical tools for interactive CAD appear feasible in the very near future on modern superworkstations with compatibility in the 20–50 MIPS range.

At present there is considerable effort to extend the utility and usability of microwave design tools by improving the user interface. This is being accomplished by adding features similar to those already available to digital designers. One example is schematic capture. This is a graphical facility for representing a circuit schematic. This would be used to produce the netlist required to describe the circuit in terms the user could understand. The trend to a more complete design capability is evident by the concern with interfaces between the simulation tools provided by microwave CAD vendors such as Compact and EEsof and the front- and back-end design entry/layout systems provided by suppliers to the digital VHSIC community, such as CADENCE, CAECO, MENTOR, VALID, and DAISY. This has raised interesting issues, primarily concerned with interfacing nonstandard tools from multiple vendors. A common means to describe hardware designs in a high-level hierarchical language is needed. Efforts are being made to develop an analog hardware descriptive language (AHDL). An IEEE Standards Coordinating Committee has been formed and has started on the AHDL. Similar effort has started in the microwave industry to define a microwave hardware descriptive language (MHDL). The analog/microwave efforts will be complementary and both will benefit considerably from the related VHDL development for the VHSIC program.

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Microwave Acoustics and Magnetics: Present and Future

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Committee MTT-2

Bulk-mode acoustic devices currently have dominance over magnetic devices in the microwave range beyond 1 GHz. The principal products to date are microwave delay lines and high overtone bulk acoustic resonators (HBAR's) [1]. Delay lines have been demonstrated up to 18 GHz and 700 ns lines using mosaic transducers have provided a broad-band (20–50 percent) match to the RF and to the bulk material. Losses in the higher frequency region (above 5 GHz), however, remain prohibitive for many applications, and this has led to hybrid designs which employ integrated amplifiers at the input and output. This approach ensures low VSWR's and compensating gain. Loaded Q values of 250 000 have been demonstrated using UHF HBAR's. The resonators are currently under intensive investigation for low-noise frequency control and filter applications. One such application is the so-called tracking filter, which provides a narrow-band window that is tunable over narrow frequency bands. Yttrium iron garnet is a low-loss acoustic material with the requisite magnetoelastic interaction to provide tunability. As depicted in Fig. 1, an externally applied magnetic field is directed perpendicular to the shear mode standing wave in the resonator. Frequency shifts of the order of a few percent have been demonstrated at S-band with 250 G.

Essential to fully integrated microwave circuits is an on-the-chip resonator which provides frequency control and filtering functions. A process compatible approach is shown in Fig. 2. A "tub" is etched in the silicon (GaAs) substrate over which is suspended a piezoelectric film such

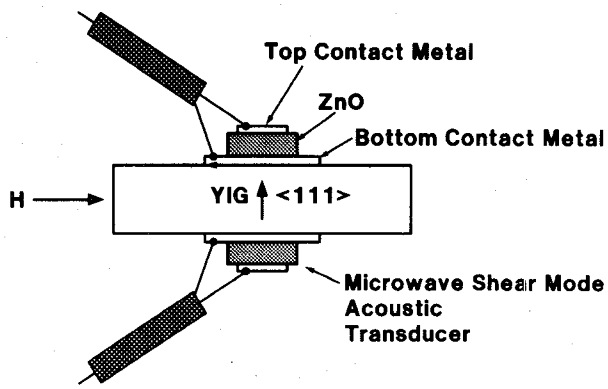

Fig. 1. YIG HBAR excited with shear waves [6].

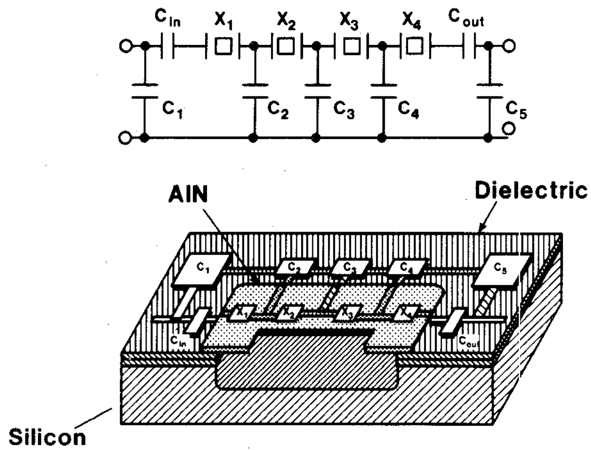

Fig. 2. Suspend film resonators provide on-chip filtering and frequency control functions [7].

as aluminum nitride (AlN) (or zinc oxide) sandwiched between patterned metal films. Circuits such as that shown in Fig. 2 have been demonstrated in the UHF–VHF frequency range.

MSW propagation in epitaxial YIG has been studied for approximately 15 years in a variety of places, and a wide variety of microwave signal-processing devices have been demonstrated [2], [3]. However, to date, MSW devices are not used in commercial or defense equipment. Initially, MSW devices were identified as performing signal-processing functions at microwave frequencies similar to those performed by surface acoustic waves at VHF–UHF. This is still a reasonable goal. However, MSW device approaches were attempted which were analogous to those used in SAW technology, i.e., periodic transducers and reflective arrays. These were inappropriate to MSW because of the strong coupling of MSW to transducers and multiple modes of propagation. Substantial progress has been achieved in recent years with the development of filtering and time-delay control techniques which are unique to MSW.

The potential applications of MSW delay lines in compressive receivers and phased-array beam steering strain the performance of the MSW in the areas of phase and amplitude accuracy, and significant further development is required in these two areas if they are to compete with alternative technologies. For example, SAW dispersive delay lines offer wider bandwidths (1.2 GHz) than have been demonstrated with MSW (1 GHz) and significantly lower phase errors. The freedom in operating frequency offered by MSW does not, in this instance, outweigh the superior accuracy of SAW devices at low microwave frequencies. The most promising area for MSW delay lines is in applications where short time delay (< 100 ns), moderate bandwidth (< 1 GHz), low loss (< 20 dB), and noncritical time delay or phase characteristics are required.

Recently, two devices have emerged which show significant promise for insertion into future electronic warfare systems. The MSW channelizers offer small size, operation at microwave IF, and, most significantly, higher dynamic range than competing technologies such as Bragg cells or compressive receivers [4], [5]. The frequency selective limiter is a unique nonlinear device which attenuates above-threshold signals while leaving small signals at other frequencies unaffected and can be used to extend the dynamic range of broad-band microwave receivers.

It is anticipated that the next few years will see a more focused development of a few MSW devices for specific system applications with increasing emphasis on manufacturability and environmental compatibility.

A new area which will see significant effort in the future is the development of nonreciprocal ferrite devices which are compatible in size and bandwidth with GaAs MMIC's. Ferrite thin-film techniques such as NiZn ferrite deposition from a sprayed aqueous solution and barium ferrite deposition by sputtering on the GaAs substrates are currently being pursued.

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Ultrafast Optics and Microwave Technology

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The year 1988 has seen many exciting developments in the application of ultrafast optics to microwave and millimeter-wave technology. Through the use of picosecond photoconductors [1] and other phase-locking techniques [2], it is now possible to generate time-synchronized pulsed or CW microwave and optical events. This capability leads to the generation, control, and characterization of microwaves and millimeter waves by picosecond or femtosecond optical techniques.

Picosecond optical pulse interaction with microwave devices and circuits provides a noninvasive probing of these devices. The characterization of microwave and millimeter-wave monolithic integrated circuits (MMIC's) using picosecond pulse sampling techniques has been demonstrated by a team from the University of Maryland and COMSAT [3]. Picosecond photoconductors are used for signal generation and sampling operations. The measured time-domain response allows the spectral transfer function of the MMIC to be obtained. This measurement technique is verified by characterization of the frequency response (magnitude and phase) of a reference 50 Ω microstrip line and a two-stage K_a-band MMIC amplifier. For the first time, a direct comparison between the results obtained by the broad-band time-domain optical measurement and those obtained from conventional frequency-domain measurements using a network analyzer has been made. The agreement is quite good. Looking into the future, this may lead to low-cost testing which allows on-wafer characterization of MMIC's before dicing the wafer into individual chips. The only electrical connection to the wafer under test is dc bias. This eliminates the need for the use of expensive probe stations used for the launching of millimeter-wave signal into the device on wafer from an external source.

A CW measurement technique using picosecond optical sampling of GaAs integrated circuits has been reported by a Stanford University group [4]. The laser pulse timing with respect to the CW microwave is provided by a phase-lock-loop feedback system which synchronizes and stabilizes the laser pulse timing with respect to the microwave synthesizer. This microwave synthesizer generates a reference signal that phase locks another RF synthesizer, which drives the acoustooptic mode locker and also provides a microwave signal launched into the circuit under test. A pulse timing accuracy of 0.3 ps has been achieved. This technique also has 2 ps time resolution, a working sensitivity of 70 $\mu V/\sqrt{Hz}$, and a spatial resolution of 3 μm. This technique has been applied to test a number of high-speed digital and analog circuits and to probe the internodes of some traveling-wave amplifiers. A similar technique has been applied to characterize the performance of a packaged 1.7 GHz GaAs planar integrated decision circuit [5]. A picosecond switching time measurement of a resonant tunneling diode has been reported by the University of Rochester and Lincoln Laboratory team. Picosecond bistable operation has been experimentally observed for the first time in a double-barrier resonant tunneling diode [6]. A rise time of 2 ps has been measured. This time-domain measurement adds necessary information to the understanding of the transport mechanisms in the resonant tunneling diode.

An electro-optic sampling technique has also been applied for high-frequency characterization of thin-film high-temperature superconducting transmission lines [7]. Distortion-free propagation of a high-current-density transient has been demonstrated. The high-frequency properties can be analyzed by careful study of the relative phase delays of the electrical transients as the temperature of the sample is varied to cover a wide temperature range, from 1.8 K to T_c.

Conversion from dc to pulsed or CW RF can also be achieved with picosecond photoconductors. Electrical transients of ultrafast rise time and large amplitude can now be generated. Picosecond and subpicosecond photoconducting dipole antennas which are capable of generating and coherently detecting picosecond [8] and subpicosecond [9] electric pulses have been demonstrated. These antennas, when illuminated with femtosecond optical pulses, radiate electrical pulses with frequency spectra extending from dc to THz. These microscopic diode antennas have been fabricated on radiation-damaged silicon-on-sapphire substrate for both transmitting and receiving. Direct dc to RF conversion using a single lateral p-i-n diode as an optoelectronic switch and a coaxial structure as a resonant cavity has been reported [10]. The electrical impulse generated by the p-i-n diode switch is coupled into the cavity via a loop antenna. The resulting magnetic field induces current in the center conductor of a voltage probe which is used to couple the RF signal out of the cavity. A monolithic dc-to-RF converter has also been demonstrated [10]. If the cavity resonator is replaced by a high-Q cavity filter, a complete CW microwave can be generated. This has been demonstrated for the generation of an optically synchronized CW 20 GHz wave [11]. For a multiple-element antenna, this technique can be used to generate phase-arrayed radiation since the RF signals are completely time synchronized with the ps optical pulses.

Looking back over 1988, there have been many applications of the ps optical technique to microwave and millimeter-wave generation and characterization.

In the future, as the technique is perfected and technology matures, we can foresee a continued merging of optics and microwaves.

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Microwave and Millimeter-Wave Monolithic Circuits

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Committee MTT-6

Over the last year, significant advancements were made in GaAs microwave and millimeter-wave monolithic circuits (MMIC's). Active devices such as the field effect transistor (FET), high electron mobility transistor (HEMT), heterojunction bipolar transistor (HBT), and diodes were integrated with passive circuitry on a GaAs wafer for small, low-cost circuits ideal for high-volume applications. Typical circuits include low-noise and power amplifiers, oscillators, phase shifters, attenuators, mixers, limiters, detectors, and prescalers.

This year, monolithic circuitry through 12 GHz was realized, with performance that was typical of discrete circuitry only a few years ago. Advancements were made which extend the frequency range of monolithic circuits far into the millimeter wave.

The key technologies which led to this advancement include new sophisticated processing equipment and techniques, as well as innovative circuit designs to exploit the monolithic process. Over the last year, extensive work was done using a direct writing electron beam (E-beam) for defining short gate lengths of 0.25 μm and under to improve and extend the frequency range of FET and HEMT MMIC circuits. Today, most monolithic circuits are manufactured with 0.5 μm FET gate lengths using photolithography processing. While gate lengths as short as 0.1 μm are now possible, the majority of high-frequency circuits have focused on the E-beam-defined 0.25 μm gate length. The ion beam has also been used to define complex shaped 0.25 μm-length gates with a mushroom shape for very high performance.

Researchers developed the necessary processes using the new type of epitaxy formation, molecular beam epitaxy (MBE), to fabricate complex semiconductor devices in MMIC form. With this process, the epitaxy layer is laid down atom by atom with precise thickness and doping density. Heterojunctions of various band gap materials, such as GaAs, AlGaAs, InGaAs, and AlInAs, can now be formed. This process is relatively slow compared to the low-cost, established ion-implanted process. The metal organic chemical vapor deposition (MOCVD) process, on the other hand, is not quite as accurate as MBE, but is a faster production process for high-volume applications. Most active devices can be processed using MOCVD with excellent performance. The metal organic molecular beam epitaxy (MOMBE) is a combination of MBE and MOCVD and is presently being evaluated.

Over the last year significant improvements and new circuits in MMIC form have been realized and are enumerated below.

A. Low-Noise Amplifiers

A complete 34 dB gain monolithic amplifier with a 1.8 dB noise figure at 10 GHz was developed which uses inductive series feedback in the source to obtain simultaneous noise match with good input match [1]. Both single-gate and dual-gate 0.5 μm-gate FET's were used with over 40 dB gain control. The use of MBE material and E-beam-formed 0.25 μm gates has resulted in a 35 GHz MMIC LNA with 6.5 dB gain and a 4 dB noise figure [2] as well as a 60 GHz LNA with 3.5 dB gain and a 6.4 dB noise figure at 60 GHz using 0.3 μm gates [3].

The HEMT offers higher gain and a lower noise figure than the FET. A super-low-noise HEMT with a mushroom-shaped 0.25 μm gate was recently fabricated using focused ion beam lithography [4]. A noise figure of 0.83 dB and a gain of 7.7 dB were achieved at 18 GHz. A complete MMIC amplifier was realized using E-beam-formed 0.25 μm gates on MBE material [5]. This MMIC amplifier recently incorporated the mushroom-shaped gate with a noise figure of 4 dB and a gain of 8 dB from 20 to 36 GHz. A three-stage HEMT MMIC amplifier using 0.2 μm gates on MBE material resulted in 10 dB gain from 42 to 47.5 GHz [6]. The most recent result using MBE-formed AlInAs–GaInAs on InP HEMT's with a 0.2 μm gate resulted in a 0.8 dB noise figure at 60 GHz with 8.7 dB gain [7].

B. Power Amplifiers

A 3 W *X*-band monolithic amplifier was developed with 13 dB gain and 20 percent power-added efficiency [8]. Dual-gate FET's were used in this two-stage MMIC to achieve gain control of 20 dB with less than $\pm 6°$ insertion phase variation. A new 14 to 37 GHz distributed amplifier was developed with 4 dB gain [9]. Over 20 dBm of power was achieved by coupling the drain of the last FET to the drain line with a capacitor. The gates were also coupled to the gate line with a capacitor.

InGaAs pseudomorphic HEMT's have produced excellent power performance with 100 mW measured capability from 35 to 60 GHz [10]. Power-added efficiency of 44 percent with 0.69 W/mm power density at 35 GHz and 27 percent power-added efficiency with 0.67 W/mm power density at 60 GHz have been realized for 0.25 μm gate length, 150 μm gate width devices. The same device with 50 μm gate width had 10 mW output with a small-signal gain of 6.1 dB at 93 GHz.

Considering high power, high transconductance, high voltage, and high power-added efficiency, the bipolar transistor has advantages over the FET. These advantages are now being extended to higher frequencies using heterojunctions of GaAs and AlGaAs. The first GaAs/AlGaAs HBT logarithmic amplifier MMIC using the MOCVD process was realized with 40 dB range from dc to 3 GHz [11]. Both p-n-p and n-p-n HBT's using MOCVD for 60 μm emitter periphery devices were successfully fabricated [12]. Power-added efficiency of 40 percent with 2 W/mm power density (0.12 W) was achieved for CW operation with 6 dB gain at 10 GHz.

C. Two-Terminal Circuits

Oscillators, phase shifter, mixers, attenuators, and switches were realized in MMIC circuits using mostly FET-based technology. Two-terminal MMIC circuits were realized using varactors and Gunn and IMPATT devices. Significant advances in these areas follow.

Dual-GaAs hyperabrupt varactors coupled to a Lange coupler in MMIC form was used to realize a 4 to 18 GHz 120° analog phase shifter with 3 dB loss [13]. Three such devices in cascade provide complete phase control. Fourteen GaAs Gunn diodes were combined in a radial combiner complete with a varactor tuning circuit in an MMIC oscillator producing 125 mW at 35 GHz [14]. Double-drift Reed IMPATT profiles were used for a varactor-tuned IMPATT MMIC oscillator producing 120 mW of power tunable from 47 to 48 GHz [15]. Finally, at 61.5 GHz, 100 mW was developed with 13.5 percent efficiency [16]. This IMPATT was monolithically combined with a varactor using air bridges to tune from 68 to 71 GHz.

D. Applications

MMIC circuits are well suited for high-volume applications such as phased array systems, missile systems, EW systems, instrumentation, communication systems (fiber optic), and consumer applications (TVRO's) where low cost and small size are paramount. Most of the circuits previously described will be combined to perform the system applications enumerated above.

For receiver applications at 26 GHz, all the MMIC chips, including the LNA, mixer, LO VCO with doubler, and buffer amplifier circuitry, were developed with 0.3-μm-gate ion-implanted processes [17]. All circuits were constructed on one side (uniplanar) using coplanar waveguide, slotlines, and lumped elements to minimize the complexity of circuits for high yield without the need for connection to the ground plane with via holes or for polished thin substrates. Combining these circuits results in a miniature receiver suitable for satellite receivers.

The ideal goal is to have all circuits on a single chip with good yield. Such a circuit was developed, a complete MMIC transmitter–receiver operational between 4 and 6 GHz which measures the distance between moving vehicles and obstacles [18]. This FM CW radar contains a VCO, modulator, RF and LO amplifiers, and a mixer on a single MMIC chip.

E. Near-Term Improvements

Improvements recently developed under the MANTEK program to reduce surface and subsurface damage of GaAs will be transferred to COMINCO, a major manufacturer of GaAs. The new material is nearly two orders of magnitude lower in these defects, which will improve circuit yield and make possible higher integration of MMIC circuits. The significant advances made in 1988 made possible by MBE, MOCVD, and E-beam lithography will continue with lower noise, higher power, and improved circuit yield. Unique applications should be expected with the MOMBE system.

Significant results should be expected for Department of Defense (DOD) systems with the Microwave/Millimeter-Wave Monolithic Integrated Circuits (MIMIC) program initiated by the DOD, which seeks to provide affordable, available, and reliable microwave and millimeter-wave circuits for use in military electronic circuits.

F. Long-Term Implications of MMIC's

Considering the progress made with MMIC circuitry to date and the vast investment being made to reduce the cost of these circuits, significant improvements will occur over the next five years. Our economy is driven in many aspects by cost. If GaAs could be made as inexpensive as silicon, one would expect to find a multitude of applications for MMIC's. Our military systems will be smarter, smaller, and lower in cost and many commercial applications will crop up with the low-cost aspects. One possibility would be to have an MMIC receiver in every household with connections from the source, a fiber-optic cable or a satellite dish, to the TV, telephone, and computer. Applications would also include high-speed logic and medical instrumentation and treatment.

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Advances in Filters and Multiplexers

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Although filters and multiplexers are often considered a "mature" subject area with little growth potential, a look at the technical literature from 1984 to 1988 indicates otherwise. Indeed, an informal count of filter papers shows a substantially greater number for 1988 than for each of the preceding four years.

The "conventional" microwave filters, many of which were described back in the 1960's, are being redesigned in printed circuit versions, with once popular solid stripline giving way to microstrip and suspended substrate stripline (SSS). The inhomogeneous nature of the latter medium has created problems for designers wishing to achieve optimum performance with a minimum of mask iterations, leading to several papers addressing the more difficult issues. Riddle [1] has offered an intriguing solution to the long-standing problem of unequal phase velocities in edge-coupled microstrip filters. Synthesis of the convenient, but analytically awkward, overlap capacitors in SSS high-pass filters has been addressed in two recent contributions [2], [3], and we have been reminded that microstrip need not be limited to quasi-TEM circuitry, but can support planar resonators as well [4].

With the continuing advances in solid-state technology, it was to be expected that the performance of voltage-tunable and switchable filters would improve as well. Examples are a 50 W tunable band-pass filter [5], a tunable band-stop filter [6], and a switched multiplexer [7]. We should expect an increase in such applications in the future.

Filters receiving the most attention in print have been those using high-dielectric-constant ceramics, particularly those in the 37–40 range with good temperature stability. These have found some use as substrates [8], and for parallel-plate capacitors. Substantially greater effort, however, has gone into using them to reduce the size of filters for 800 MHz mobile telephone service: both for miniature TEM resonators for the mobile sets [9] and for higher order mode cavities for base stations [10]. Success in these applications requires precision in the forming of the materials and the selective metallization of their surfaces. Higher frequency applications permit the use of dielectric resonators in more manageable shapes, such as rings and rods, usually without the necessity for metallization [11]–[13].

The critical importance of economy of size and weight for satellite communications has fueled a seemingly endless drive for using the same space over again with multimode filter cavities. Whereas a decade ago dual-mode cavity filters were the norm, today dual-mode is being applied to dielectric resonator cavities [14], [15], and triple- and quadruple-mode cavity filters are becoming common [16]–[19].

Millimeter-wave activity, which has been "just around the corner" for the past 25 years, has at last arrived. In the filter world this has created a need for practical alternatives to complex and ultraprecise electroformed waveguide filters. Although printed circuit techniques such as SSS generally ease the fabrication problems, their quasi-TEM nature makes them too lossy for most applications. *E*-plane filters, on the other hand, which are similar to finline in having the most critical dimensions on chemically etched inserts, appear to offer the best compromise between manufacturability and performance for frequencies below 100 GHz [20]–[23]. Another approach, with potential for even higher frequencies, is the use of dielectric waveguide in its various forms. Most of this effort appears still to be in the R&D stage, but several band-pass and band-stop filters have been built [24]–[26].

We must also mention filters which, for historical reasons, have not fallen within the purview of this committee. SAW filters have long been available for highly selective (and high-loss) responses at low frequencies, but an 800 MHz SAW duplexer with passband loss near 1 dB should be noted [27]. In the field of magnetics the ubiquitous YIG sphere filter is now being supplemented by magnetostatic wave (MSW) devices employing YIG film which can be patterned by photolithography. This permits complex circuits, such as a 13-channel MSW filter bank in *S*-band [28]. The advent of monolithic circuits puts special demands on filters, which cannot easily be miniaturized without unacceptable losses. Practitioners at Texas Instruments have, nevertheless, reported a monolithic switched preselector with respectable performance [29]. The filter approach with the greatest promise for monolithics, however, may well be the microwave active filter, as described by Rauscher [30].

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Microwave and Millimeter-Wave Packaging

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One of Sonny Maynard's main contributions to the microwave community may have been his observation at the start of the MIMIC program that, "We are developing $2 chips in $20 packages that require $200 worth of testing." The state of the art of the design, development, and fabrication of GaAs IC's has progressed amazingly over the 12 years or so that work in this area has been under way. It has been demonstrated that at least one of almost any circuit imaginable can be built and tested, and the results published, limited only by the physical limitations of the MMIC medium and the persistence of the processing team. The realities of high-volume production have also been demonstrated, with many companies successfully shipping hundreds of thousands of GaAs IC's. The state of the art of the packaging of these chips, however, has not progressed quite as rapidly.

If we look for a minute at the costs of making and packaging IC's, we find that today the cost of packaging outweighs the cost of chip manufacture in almost all cases. Fabricated, dc tested 3-in-diameter GaAs wafers are available from a number of foundries for around $5000. After subtracting some area around the edge of the wafer due to various edge effects and for test patterns and alignment marks, a good rule of thumb is 0.63 cents per picoacre ($1.57 per square mm for those of us still mired in metric) of processed GaAs. This means that a 1 mm square chip, on which companies have demonstrated complete receivers, high-isolation switches, power amplifiers, and low-noise amplifiers, can be built for $3.16 assuming a 50 percent yield, which is readily achievable these days. If we package this chip in what is rapidly becoming an industry standard for applications up to 5 GHz or so, an eight leaded, glass package measuring 0.18 in on a side, we find that the package costs $2.50 in high volume (100000 pieces), the lid costs $0.25, and assembly, inspection, and dc testing come in at about $4.00. As we go higher in frequency the chip cost goes up slightly as smaller gate length and tighter tolerances take their toll on yield, but packaging cost can rise dramatically. Simple ceramic packages, useful to about 10 GHz, can cost from $7 to $9 in high volume and more clever ceramic packages, which are useful to 20 GHz, can cost from $35 to $75 and up and are sometimes difficult to acquire in high volume. Custom ceramic high-frequency packages can also come equipped with tooling charges from $20000 to $40000.

The requirements on high-frequency (or high-speed) packages are numerous. These should include at a minimum:

- low insertion loss and VSWR for RF leads,
- high isolation between leads,
- hermetic sealability,
- mechanical ruggedness,
- low thermal impedance,
- low cost in reasonable volumes,
- capability to meet MIL-883B specifications,
- compatibility with microstrip,
- availability from multiple sources,
- ability to be readily bonded,
- compatibility with automated assembly equipment.

The technologies required to design and fabricate these packages in volume at low cost bring together a number of different disciplines: system design to visualize the usage, microwave design to ensure performance, CAD for three-dimensional modeling, ceramics and metallurgy to develop the required materials and metallization schemes, and automated assembly and testing to ensure low-cost fabrication and usage of the packages. Most radar and EW system manufacturers have efforts under way to develop inexpensive, high-volume packaging for GaAs IC's in their systems and many IC manufacturers are also dabbling in package design. Results of this research, however, are often considered proprietary and remain unpublished or shown only in closed conferences, such as MANTECH. If we look at the packaging papers published over the last few years in the major microwave wave IC conferences, we find, at the GaAs IC Symposium, two packaging papers in 1985, two in 1986, and none in 1987. At the Microwave and Millimeter-Wave IC Conference there were none in 1985, 1986, and 1988 and three in 1987. At the complete MTT Symposium in 1988 there was not a single packaging paper among the 250 microwave papers given.

Much of the material which has been presented is innovative and potentially useful. Harris has published numerous papers on packaging which include descriptions of modified TO-3 and TO-8 packages which work to 18 GHz [1] and should be inexpensive in volume. Included were multilayer ceramic leadless chip carriers [2] which are uesful for both microwave and digital applications and have been used to 20 GHz. Harris has also shown an interesting structure called WAFFLELINE [3] which can be used to integrate GaAs microwave or digital IC's. It consists of a base which has a waffle-iron-shaped grid etched into it. Into the channels of the grid are placed dielectric-coated wires which carry the RF and dc signals between chips and to the outside world. Over the wires and the grid is placed a layer of foil to isolate the unit. The IC's are placed on top of the grid and connected to the wires which protrude from the channels. Tektronix has published a novel surface mount package [4] which uses etched and metal-filled via holes through a ceramic substrate to bring RF, dc, and ground leads from a coplanar type structure on the bottom of the package to microstrip on the interior of the package. Good performance is achieved to 18 GHz at a cost of about $39. In terms of packages for GaAs digital circuits, the Mayo clinic has been a leader, publishing a number of papers on packages fabricated of beryllia and copper/polyimide [5] with pin counts as high as 216 which operate to frequencies as high as 8 GHz. Tachonics, an IC manufacturer, has worked jointly with two package vendors to develop and fabricate (open tooled) a 20 GHz package using cofired ceramic with a copper/tungsten base for good thermal dissipation [6]. These packages are available in high volume for under $10 and are suitable for a wide range of GaAs IC's.

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Microwave and Millimeter-Wave Ferrite Technology

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Normal operation of microwave ferrite devices is achieved when the ratio of the saturation magnetization of the ferrite in kilogauss to the operating frequency in GHz is in the range 0.1 to 0.2. Using a material with a saturation magnetization higher than suggested results in sharply increased magnetic losses while using a lower saturation magnetization results in a longer device with increased conductor and dielectric losses as well as increased size and weight. Ferrite devices such as circulators, tunable filters, and phase shifters are not "material-limited" in the microwave range, say 2 to 20 GHz, but are "material-limited" in the millimeter-wave range. Consequently, most

TABLE I
FOUR-SPHERE FILTER PARAMETERS

Frequency Band (GHz)	Insertion Loss (dB) Min.	Insertion Loss (dB) Max.	Off-Resonance Isolation (Typical)	3 dB Bandwidth (MHz) Min.	3 dB Bandwidth (MHz) Max.	Magnet Power (W) Min.	Magnet Power (W) Max.
26.5–40	11.0	14.0	> 75 dB	120	200	0.27	4.70
33–50	10.0	13.0	> 75 dB	180	250	0.26	7.10
40–60	8.0	12.0	> 75 dB	180	270	0.28	8.40
50–75	8.0	12.0	> 70 dB	190	300	0.35	12.00

research and development activity is concentrated at the millimeter-wave frequencies. One result of this is the use of spinel ferrites to extend the upper frequency limit of the common microwave ferrite devices. Hexagonal ferrites are being used for magnetically tuned circuits to keep bias fields at realizable levels. Finally, some basic measurements on material properties are being conducted well into the millimeter-wave frequency band.

Spinel ferrites have been used to construct circulators/isolators, twin toroid phase shifters, and dual-mode phase shifters in the 20–100 GHz range. Electro-Magnetic Sciences (EMS) of Norcross, GA, have both fixed bias and switchable junction circulators in this range with insertion loss of the order of 0.2 dB or less. Microwave Applications Group (MAG) of Santa Maria, CA, has demonstrated a dual-mode phase shifter operating at 60 GHz with an insertion loss of 1.5 dB, while EMS has demonstrated about the same level of insertion loss at 60 GHz with the twin toroid phase shifter.

An innovative approach for using spinel ferrites at millimeter-wave frequencies was described by Dionne *et al.* [1] of the MIT Lincoln Laboratory. A Faraday rotator was realized for a beam waveguide. The rotator provided 45° rotation over a 20 percent band with an insertion loss of less than 0.1 dB. Since commercially available Faraday rotation isolators operating in the same frequency range in waveguide have insertion loss of the order of 1 dB, the advantage is obvious. Although the frequency of operation was only 35 GHz, scaling to higher frequencies is straightforward and only a nominal penalty is incurred since conductor losses are eliminated.

Hexagonal ferrites have long been considered candidates for application in the millimeter-wave range because their large anisotropy field greatly reduces the magnetic bias field required for ferrimagnetic resonance. Magnetically tunable bandpass filters using two hexagonal ferrite spheres have been demonstrated to cover full waveguide bandwidths through *W*-band. D. Nicholson of Hewlett-Packard Company, Santa Rosa, CA, recently described a new design using four hexagonal ferrite spheres along with an intermediate waveguide coupling network to improve the off-resonance isolation [2]. Reported results are shown in Table I.

Afsar and Button [3], working at the MIT Bitter Magnet Laboratory, have observed natural ferrimagnetic resonance at 240 GHz in hexagonal ferrite. Induced ferrimagnetic resonance was observed at 210 GHz in a spinel structure using an external field of 75.3 kG. Afsar and Button also describe a direct measurement technique for the complex permittivity and permeability of materials up to 400 GHz.

General Trends

Obviously the general trend in ferrite device development is toward higher frequencies. The evolutionary development of circulators and phase shifters using spinel ferrites will continue, although devices using this approach will probably find application only at frequencies below 100 GHz. Development of tunable filters using hexagonal ferrites will result in useful components up to 100 GHz.

Another trend is toward the development of planar ferrite devices, particularly in the millimeter-wave range. Workers in Europe continue to pursue finline geometries for isolators, circulators, and tunable filters [4], [5]. In the U.S. limited research is being conducted on planar geometries for phase shifter application [6]. Workers in Japan have developed an electrically steerable leaky wave antenna at 50 GHz using a corrugated ferrite dielectric slab waveguide [7].

Future Advances

Since the volume of ferrite material decreases as the operating frequency increases, ferrite manufacturers have little incentive to develop materials with higher saturation magnetizations for use at millimeter-wave frequencies. However, a high-magnetization NiZnMn spinel ferrite has recently been developed by Trans-Tech Inc. of Adamstown, MD, which provides a saturation magnetization of about 5000 G with a square hysteresis loop and good dielectric properties. Further developments in the spinel ferrite materials will be limited to different manufacturing approaches and improved process control. The use of hexagonal ferrites will be minimal because of the lack of commercially available materials. None of the leading suppliers of ferrite materials offer hexagonal ferrites in their product lines.

Device development at millimeter-wave frequencies will continue at a slow pace. The common elements are now available up to 100 GHz and circulators have been developed at even higher frequencies. Continuing efforts to develop components in a planar geometry will result in new realizations of those functions best performed by ferrite devices—circulation, phase shifting, and switching.

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Microwave Systems 1988

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Advances in the microwave systems area can be spurred from two directions: from external demands placed on systems to perform new or extended functions and from internal progress in the technology base, which generally results in improved performance. After briefly considering some demands, this review will summarize recent advances in the technology base which particularly affect military applications as well as communication systems.

In military systems, demands derived from defense strategies and initiatives have historically shaped system designs; currently, however, the advent of microwave integrated circuits is creating the basis for demands which lead developments into new directions. In communication systems, the demand for an integrated services digital network (ISDN) [1] has recently emphasized the importance of digital connectivity and requires increased information densities from transmission systems. In response, system architectures and performance requirements have been modified. Such external demands frequently shape the directions in which advances in system design and performance occur.

Military applications of microwave systems span a wide range of the spectrum and include both mature and state-of-the-art technologies and system architectures. These applications include command, control, communications and intelligence (C3I) systems as well as surveillance and missile guidance applications.

The Global Positioning Satellite (GPS) System integrates a number of mature *L*-band microwave technologies with sophisticated signal coding concepts to transmit waveforms whose information content and time of arrival can be processed to yield receiver position and velocity coordinates. Miniaturization of receiver components is expected to provide hand-held systems for eventual tactical military use. Position accuracy, while a complex function of variable satellite geometry and atmospherics, is on the order of a few meters.

At the higher end of the microwave spectrum, the MILSTAR system uses a *V*-band traveling wave tube, IMPATT diode, and GaAs FET technology in ground terminals and in satellite-borne repeater terminals for worldwide communications of both analog and digital information. Spanning low to high ends of the microwave spectrum, electronic warfare systems are benefiting from multioctave active components made feasible by GaAs MMIC technology. Shorter millimeter-wave systems, while they have still not quite emerged from their long incubation period in a "just around the corner" status, are enjoying significant development support for missile and munitions guidance and antiarmor applications.

The classical military system application of microwave technology, i.e., radar, has evolved into large phased arrays. These have been deployed as mobile tactical air defense systems in the form of PATRIOT, a 5000 element *C*-band space-fed lens antenna powered by a crossed field amplifier transmitter. They have been deployed on shipboard, at *S*-band, in the form of the AEGIS SPY-1 Radar, and as large, fixed UHF arrays such as PAVE PAWS for long-range surveillance functions. The beam agility available from these inertialess electronically steered systems, coupled with digital computers for both control and signal processing, provides multiple functions for simultaneous tracking and engagements of large numbers of radar targets.

More futuristic systems in the demonstration/validation phase of development include integrated electronic warfare systems (INEWS's) as well as integrated communications, navigation, and identification avionics (INCNIA). These utilize a common aperture to combine multiple avionics functions on board Air Force and Navy advanced tactical aircraft in the interest of reduced size, weight, cost, and radar cross section, while simultaneously improving capability.

A major new Defense Department Initiative, the Microwave/Millimeter-Wave Monolithic Integrated Circuit (MIMIC) program [2] entered phase 1 with four teams of contractors sharing $2000M for the development of a variety of GaAs subsystem chips, including T/R modules for active arrays, broad-band amplifiers, switches, and frequency converters for EW receivers and jammers, communications, and smart munitions systems.

Some of the recently reported technology benchmarks which support and extend the systems applications described above are described as follows:

A transmit/receive module capable of delivering 2 W for an *S*-band phased array radar has been developed using a hybrid MMIC/MIC approach [3]. Five MMIC subassemblies provide a 4 bit phase shifter, a two-stage low-noise amplifier with a noise figure less than 4.0 dB between 2.7 and 3.3 GHz, driver and power amplifiers, and T/R switching. An integral thick-film control hybrid provides voltage regulation, T/R switch, and phase shifter settings, interfacing with an external fiber-optic control link.

An MMIC frequency converter with an RF bandwidth of 8–15 GHz with an IF bandwidth of 1.5 GHz and minimum of 12 dB conversion gain has been reported. The 48 mil × 96 mil chip includes a two-stage RF amplifier, two-stage LO buffer amplifier, double balanced mixer, and three-stage IF amplifier [4].

MMIC distributed amplifiers using MESFET's have demonstrated modest power multioctave performance with excellent noise figures (100 mW, 2–20 GHz, 6 dB NF, and 7 dB associated gain) [5] while more recent implementations using high electron mobility transistor (HEMT) devices have been reported with improved noise figure and associated gain of less than 5 dB and better than 10 dB, respectively [6].

Broad-band switches using GaAs FET 0.35 μm gate MMIC technology are capable of dc–40 GHz performance with less than 3 dB of insertion loss and 23 dB of isolation [7]. Over a more "modest" 20–40 GHz spectrum, the insertion loss is under 2 dB while the isolation exceeds 25 dB. Power handling capability is on the order of 15 and 20 dBm, respectively, while switching times are less than 500 ps for both the dc–40 GHz and 20–40 GHz models.

Computer-aided design techniques are absolutely essential to the MMIC technology as it integrates active devices, transmission structures, and passive components, often in nonlinear operating conditions. These were highlighted in a special issue of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES in February 1988 [8].

Projections of the performance of high-speed digital integrated circuits is the subject of a tutorial review article in the March 1987 issue of the MTT TRANSACTIONS. These devices are expected to form a bridge between microwave and signal processing technologies, with direct processing of signals as high as 4 GHz foreseen [9].

Communication systems are affected by advances in the technology base on a number of different levels. Component or device level advances tend to yield incremental performance improvements; subsystem level advances tend to result in economic advantages or architectural changes; while overall system advances result from improved system modeling (software) or manufacturing technologies. Specific progress on these three levels is discussed below.

Advances in device performance have affected both the transmission and the information processing capabilities of systems. Further improvements in the performance of HEMT's have resulted in a reported noise figure as low as 0.68 dB at 12 GHz, with an associated gain of 9.7 dB [10]; octave bandwidth operation has been achieved over 20–40 GHz with a noise figure of 5 dB and associated gain of 6 dB [11]. With specially designed structures, HEMT devices have been demonstrated with output power densities of 0.85 W/mm at 55 GHz [12] and initial reliability data indicating a MTTF of one million hours [13].

While high-frequency operation with large-scale integration can be expected from GaAs on Si heterojunction bipolar transistors (HBT's), only limited performance data have been published [14], [15]. In contrast, GaAs MESFET's show excellent results as a low-noise amplifier at V-band ($NF = 6.4$ dB with $G = 3.5$ dB) [16], as a high-power amplifier (1 W with $G = 5$ dB at 34 GHz) [17] as well as for high-speed digital signal processing in a 7 Gbit/s dynamic decision circuit [18].

Advances in the performance of integrated circuits (IC's) affect systems on both the component and the subsystem level (a summary of commercial applications of GaAs IC's is given in [19]. The extent to which system functions are integrated onto a single chip depends greatly on both technological and economic factors. With the trend continuing toward higher levels of integration, implementations will depend mostly on progress in wafer yields. At this time, reported results range from a three-stage HEMT amplifier which provides a gain of 16 dB at 44.5 GHz and includes on-chip matching [20] to a fully integrated, 30 GHz satellite transponder with a weight reduction to approximately 1/3 relative to that of a hybrid transponder [21].

In digital signal processing at rates reaching into the microwave region, a number of separate chips are used to implement a transmitter and receiver for an optical transmission system operating at a rate of 4.5 Gbit/s [22]. System integration of a regenerator operating at 2.4 Gbit/s has been demonstrated for ISDN applications [23]; LSI versions of serial-to-parallel converters perform in the 1 GHz range [24]. These results support the trend toward digital signal processing at microwave rates where HBT devices may play an increasingly important role due to their more mature technology base.

Advances on the system level have demonstrated a terrestrial radio relay system with an information rate of 400 Mbit/s using 256 QAM signaling [25] and mobile communications via satellite for analog and digital information transmission [26], [27]. Designs of these systems require many of the advances described above, but also rely on the improved accuracies available in modeling software. Of special importance are recent advances in nonlinear modeling which allow characterization of intermodulation noise.

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HIGH-T_c SUPERCONDUCTORS FOR MICROWAVE APPLICATIONS

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Since the first sign of superconductivity was discovered in mercury at 4.2 K in 1911, substantial efforts have been expended over the years to find materials with higher transition temperatures and to investigate applications that take advantage of those unusual material properties. Superconductivity is characterized by the fact that the dc resistance at a particular temperature becomes zero. For RF applications this is not completely true; typically, at liquid He temperatures a good low-T_c superconductor, such as niobium, operating at *S*-band, may have a surface resistance approximately three orders of magnitude lower than copper at the same temperature. This surface resistance changes with temperature and frequency and does limit the ultimate performance achievable with low-T_c superconductors. Nevertheless, a large number of electronic applications have been developed around these materials,

TABLE II
LOW-T_c MICROWAVE APPLICATIONS

S.C. Component	Application
Ultra-High-*Q* Cavities	Linear Accelerators Frequency Standards
Low-Loss Transmission Lines	Low-Dispersion Delay Lines Matching Filters
Josephson Junctions	Squids (High-Sensitivity Detectors) Parametric Amplifiers High-Speed Switches A/D Converters Mixers

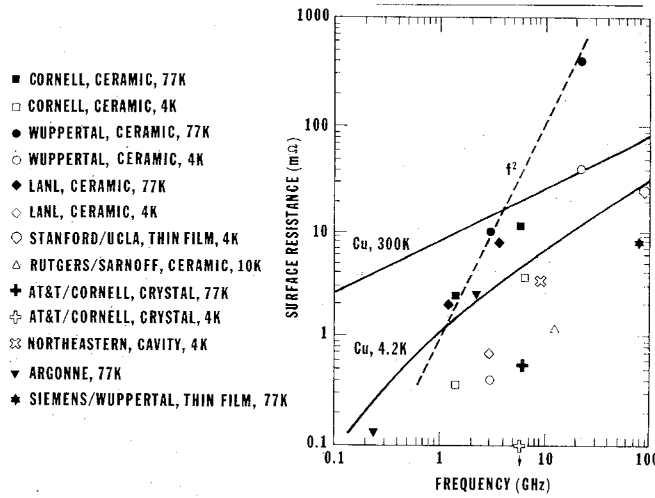

Fig. 3. Summary of state-of-the-art superconducting materials.

as shown in Table II. In most cases, widespread use has been hampered by the very low temperatures required, and only in applications where the improved performance due to superconductivity is absolutely essential, such as in radio astronomy, particle accelerators, high-speed instrumentation, and medical sensing, has low-T_c superconductivity reached commercial success.

This situation changed drastically with the discovery in 1986 by Bednorz and Muller [1] of superconductivity above 30 K and the ensuing avalanche of research activities that led to transition temperatures of several materials in the 100 K range.

With cooling requirements greatly reduced, a number of superconducting microwave applications may become economically feasible. Most of the performance capabilities currently quoted by materials researchers relate to transition temperature, maximum current density, and magnetic flux dependability. For microwave purposes the most important performance parameter is the surface resistance, which is much less readily known. Fig. 3 shows a summary of state-of-the-art materials [2] as quoted by various sources. Bulk materials, due to their relatively porous consistency and poor surface condition, are not ideal microwave conductors. Typically the best bulk materials [3], [4] of the 123 compound show a surface resistance equal to that of copper at liquid nitrogen temperatures and approach values an order of magnitude lower at temperatures between 5 and 20 K. Much better performance has been

TABLE III
EXAMPLES OF PASSIVE MICROWAVE APPLICATIONS OF HIGH-T_c SUPERCONDUCTORS

INTELLIGENCE	ELECTRONIC WARFARE
Channelized Receivers (Multiplexers, Channel Dropping Filters)	False Target Generators (Variable Delay Lines)
RADARS	COMMUNICATIONS
Phased Arrays (Delay Lines, Oscillators with Utralow Phase Noise, Low-Loss Feed Networks, Matching Filters)	Multiplexers, Filters, Ultralow Phase Noise Oscillators

TABLE IV
MAJOR CHALLENGES IN THE APPLICATION OF HIGH-T_c THIN-FILM SUPERCONDUCTORS TO PASSIVE MICROWAVE COMPONENTS

Substrate compatibility	Current density limits
Buffer layer for proper growth	Magnetic field sensitivity
Surface resistance	Patterning and contacts
Adherence and uniformity	Passivation and environmentalization

obtained from single-crystal 123 material, as illustrated by the AT&T crystals measured at Cornell [5]. Thin-film surface resistance measurements are so far rather sparse due to unavailability of uniform, reproducible samples of sufficient size for meaningful measurements. The best results are those reported by UCLA [6] at 100 GHz and most recently by the University of Wuppertal [7] at 87 GHz, which indicate very promising performance possibilities if scaled to the lower microwave range. The newer thallium- and bismuth-based compounds have so far not seen much microwave evaluation but look promising because of their higher T_c.

For the near future, the most likely applications in the microwave area will be in passive components which take advantage of the lower losses that superconductors promise to offer. In principle, superconducting components could be configured that have either such smaller size and weight than conventional components, or much better performance than is obtainable with current technology. Filters, matching networks, delay lines belong into the first category, while ultra-high-Q resonators and very low phase noise oscillators, for example, fall into the second category.

A number of promising passive superconductor applications are shown in Table III. Similarly, superconductivity can also be expected to lead to major improvements in active devices [8], although the time frame for their practical introduction will likely be much longer due to additional process restrictions. The high annealing temperatures currently used are generally incompatible with semiconductor technology.

Major efforts are now being directed to study the effects of surface conditions and grain boundary contacts on surface resistance. Also, the need for producing good thin-film superconductors on substrates that are compatible with low-loss microwave propagation is becoming more universally recognized. A number of important characteristics that the new materials should fulfill for microwave superconductor applications are given in Table IV. We are obviously just at the beginning of a very challenging period. However, the extremely rapid movement in materials technology forced by countless universities and laboratories leads one to expect the availability of superconductors suitable for microwave applications within the next two years.

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