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GUIDED WAVE PHENOMENA
IN
MILLIMETER WAVE INTEGRATED CIRCUITS AND COMPONENTS

FINAL REPORT

by

Tatsuo Itoh

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The University of Texas at Austin

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BSTRACT (Continue on reverse if necessary and identify by block number)

Representative projects under support of DAAL-03-88-k-0005 from Army Research Office are summarized in this report. Following the narrative descriptions with appropriate illustrations, a complete list of articles published in scientific journals and those presented at national and international conferences is provided. Lists of personnel and advanced degrees are also included. The projects were carried out at The University of Texas at Austin and later at UCLA.

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ABSTRACT

Representative projects under support of DAAL-03-88-K-0005 from Army Research Office are summarized in this report. Following the narrative descriptions with appropriate illustrations, a complete list of articles published in scientific journals and those presented at national and international conferences is provided. Lists of personnel and advanced degrees are also included. The projects were initially carried out at The University of Texas at Austin and later at UCLA.

1. INTRODUCTION

As the frequency of operation is increased toward millimeter-waves and beyond, conventional microwave circuits and design concept will face a number of difficulties. For instance, the capability of many solid state devices will deteriorate and hence they must be placed in a best possible electromagnetic environment in which the interactions of devices with the electromagnetic field are maximized. In some cases, the physical dimensions of microwave solid state devices are no longer small with respect to the wavelength and the distributed effect in the device must be taken into account or must be utilized intentionally.

Passive components also deteriorate as the frequency is increased. For instance the insertion loss increases with frequency and the scattering at discontinuities become more complex due to onset of leakage and radiation and nonproximity coupling. Transmission lines, particularly in monolithic integrated circuit format, require fresh look. Choices for transmission lines for particular tasks should be increased and an analysis for such needs to be established.

Under support of DAAL-03-88-K-005 from Army Research Office, a number of projects addressing the issues described above have been investigated. The narrative portion of this report presents only the highlight of projects which are divided into several sections. The complete record of accomplishment is provided in the form of List of Publications.

2. ACTIVE INTEGRATED ANTENNAS AND QUASI-OPTICAL COMPONENTS

It is well known that the output of solid state oscillator will degrade as the frequency of operation is increased. One way to combat this problem is to power combine the output of the individual oscillator. However, if the device level or circuit level combining is used, it is difficult to combine a large number of oscillator. For the output power comparable to vacuum tube, hundreds or thousands solid state oscillators need to be power combined. Quasi-optical power combining is a very promising technique to accomplish this requirement. In addition, the quasi-optical technique can be used for receiving and controlling millimeter-wave signals.

There are several topological classes for quasi-optical power combining. Fig.1 illustrate the classification. In the present project, our efforts have been concerned with the injection locking type or strongly coupled type under the array type format. Our intention is to create a truly planar configuration without any external locking mechanism. However, to do so require certain penalty. For instance, the circuit for our types are more complex because all the locking mechanism must be in the planar or layered configuration. On the other hand, the added complexity of individual oscillator structures may open up possibilities for using a single element or a small array for applications other than quasi-optical power combining. Some of the possible non-power applications are personal communication, telemetry, and noncontact sensors. In what follows, we list some of the highlighted accomplishments. A great emphasis has been placed on the topology of the power combining configuration, more efficient and robust active antennas, element level combining in addition to spatial power combining, and understanding and theoretical analysis of the structures. Representative references are indicated by the numbers from List of Publications.

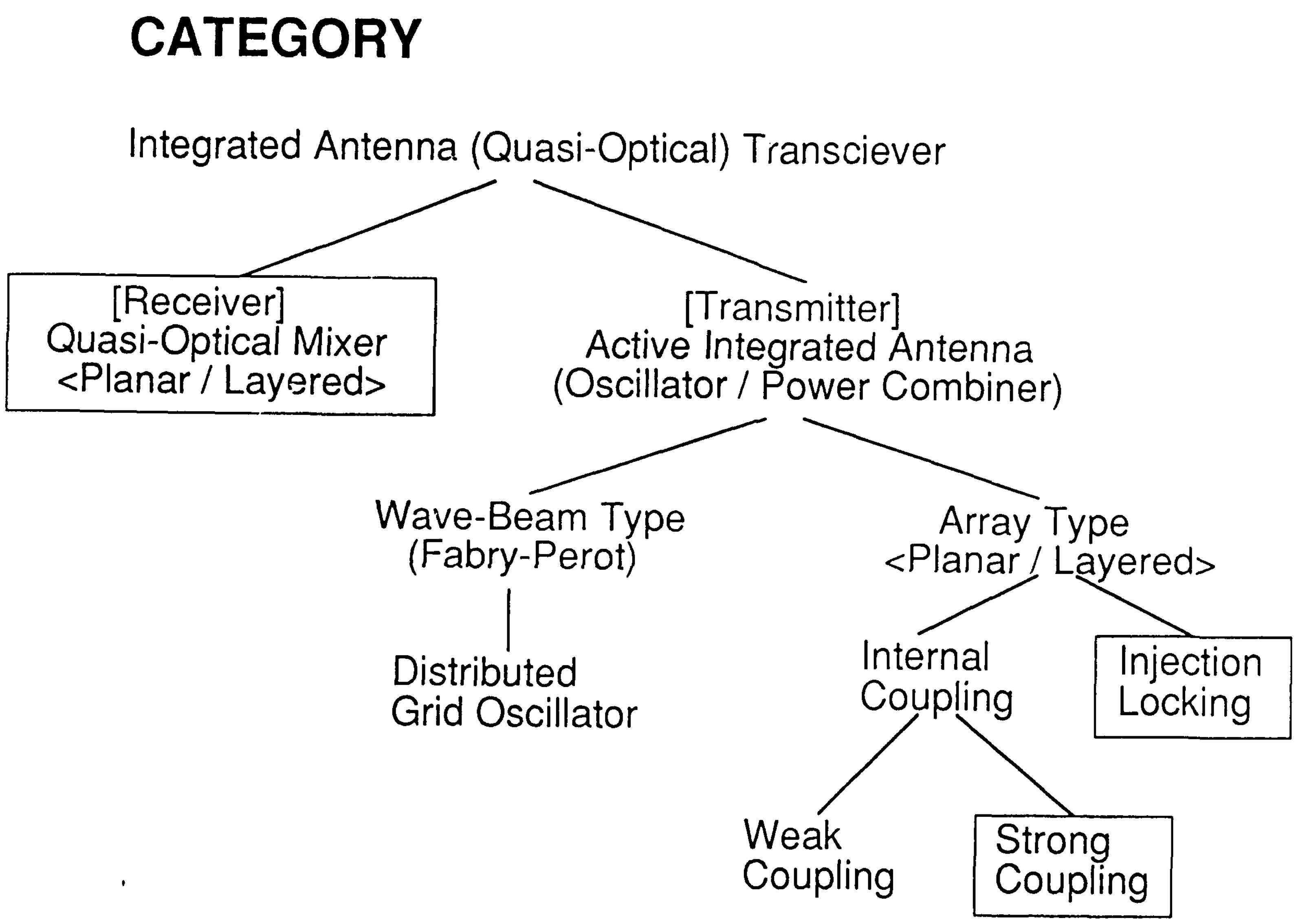


Fig.1 Classification of quasi-optical structures

2.1 Leaky wave stop band oscillator [J5, J6, J7]

It is known that a leaky wave antenna made of a periodic structure experiences the leaky wave stop band at the frequency for which the guide wavelength is equal to the period. At such a frequency, the input impedance of the antenna becomes reactive due to a "resonance" phenomenon so that the radiating efficiency becomes very poor. In the current project, this phenomenon undesirable for antenna applications is intentionally used for providing a frequency dependent feedback to an active devices connected to the input terminal of this antenna. Therefore, the antenna is not only used as a radiator but also as a resonator to provide frequency selectivity of the oscillator. Fig.2 shows a realization by means of a microstrip structure with measured results of the radiation pattern.

This concept has been extended to more complex configurations which enable power combining of two devices from a single antenna as well as to generation of second harmonics.

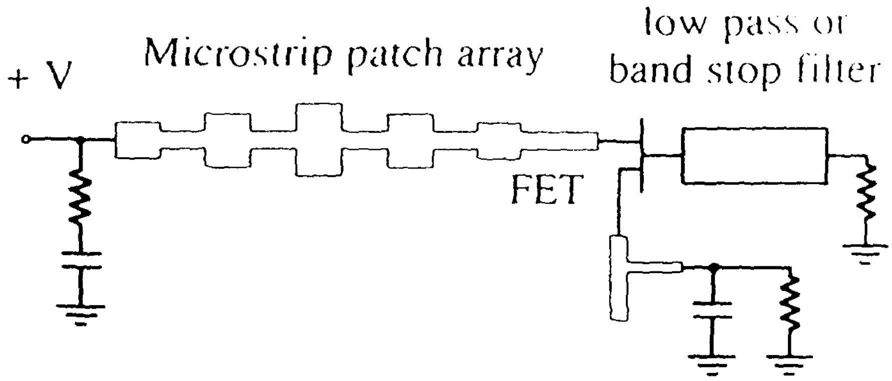
2.2 FET based feedback type quasi-optical oscillator [J15, J19]

Instead of a negative resistance configuration, an oscillator can be formed by a feedback applied to an amplifier. Typically, this configuration allows a much wider injection locking bandwidth. These oscillators can be connected in a sequential fashion for quasi-optical power combining as shown in Fig.3. At a 6 GHz design, the locking bandwidth was 500 MHz and the effective radiating power was 4 W for the dc input of 750 mW. As the frequency is changed within the locking bandwidth, the output beam can be spatially scanned at a rate of 7 degrees/100 MHz.

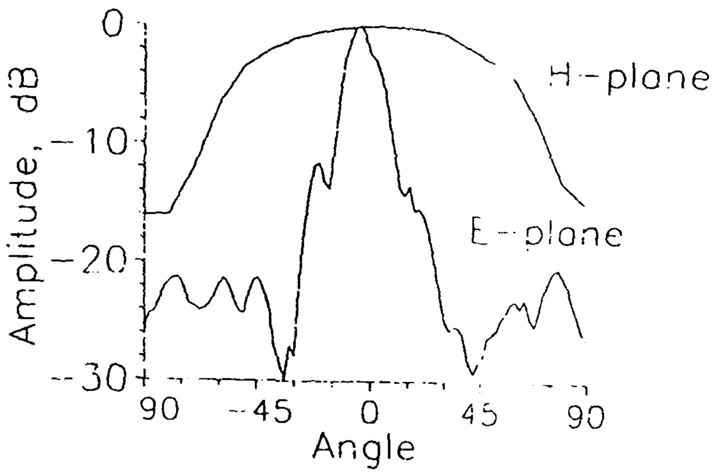
These oscillators (active antennas) can be connected in parallel by way of Wilkinson power combiners for quasi-optical power combining. As shown in Fig.4, this structure has a 3-dimensional construction so that the efficiency of the microstrip antenna can be increased by controlling the substrate for the antenna without significantly affecting the circuit side performance. This 4 x 4 array has been operated at 6 GHz with an effective radiating power (ERP) of 28.2 W CW and an isotropic conversion gain of 9.9 dB. The locking bandwidth was 7.5%.

2.3 Slot and CPW based multi-level integrated active antennas [J24, J26]

The so-called uniplanar technology is useful for monolithic integrated circuits for the future. The basic configurations are based on the slot line and coplanar waveguide (CPW). Therefore, the circuit can be formed only on one side of the substrate or can be distributed on both sides of the substrate. This topology has been extensively studied for applications to active integrated antennas and quasi-optical power combining. Fig.5 shows the basic concept involving the slot radiator on one side of the substrate and microstrip circuits on the other side. This configuration may lead to a futuristic wafer scale integration. A number of circuits have been studied based on this concept. Some examples are (1) reactive loading of the slot antenna for electronic tuning over a relatively wide frequency range [C45], (2) slot amplifying and slot oscillator [C43], (3) a 20 GHz 2 x 2 slot oscillator array [C57], (d) a 40 GHz second harmonic active antenna [C61], and (e) non-periodic 6-element power combining array for wide band applications [C62]. Fig.6 shows an example. In a periodic array, the periodicity increases the Q of the system. On the other hand, if the array is non-periodic, the Q can be lowered so that the oscillation frequency can be tuned in a wider range and the design can be more robust. In the case of the example in Fig.6, the tuning

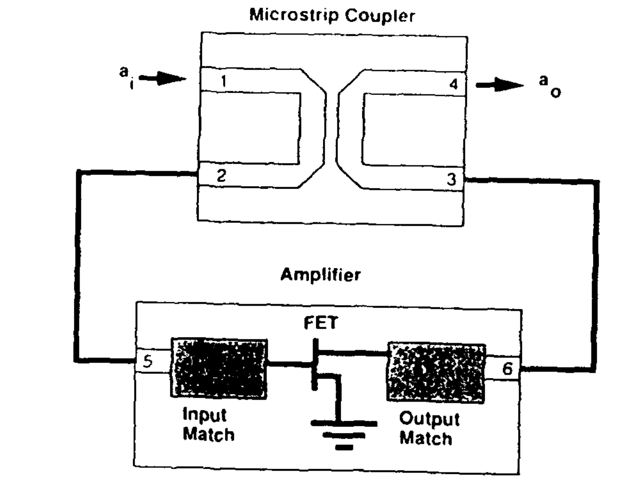


Schematic view of single-device oscillator circuit



Radiation patterns for single-device oscillator with 17-element antenna.

Fig.2 Leaky wave antenna transmitter



Schematic diagram of two port oscillator.

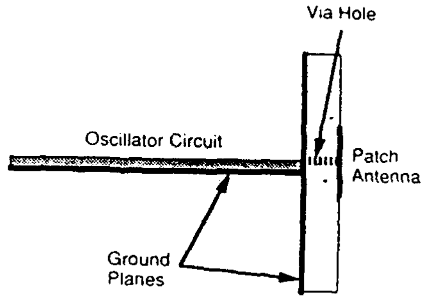
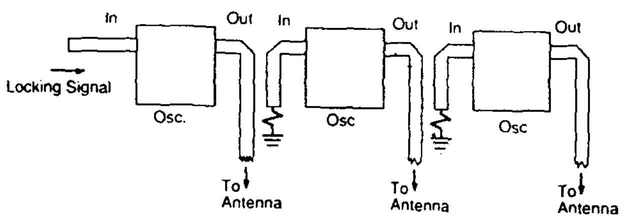
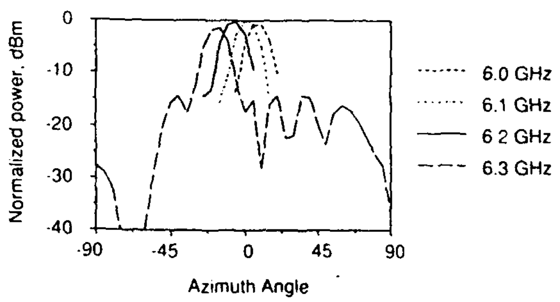


Illustration of antenna connection to oscillator circuit.

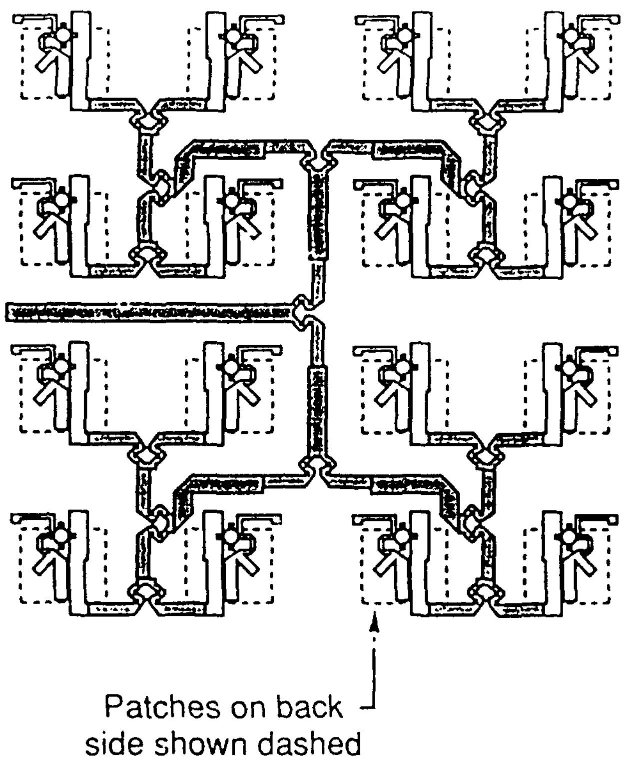


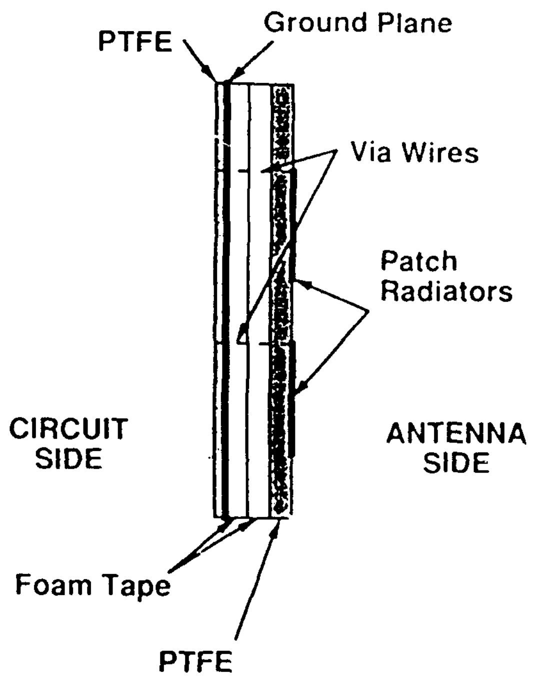
Series array of injection locked elements.



Antenna pattern for five element oscillator array.

Fig.3 Feedback type active antenna and sequential array





Side view of the array, showing the layered structure.

Fig.4 4 x 4 injection locked quasi-optical power combining oscillator

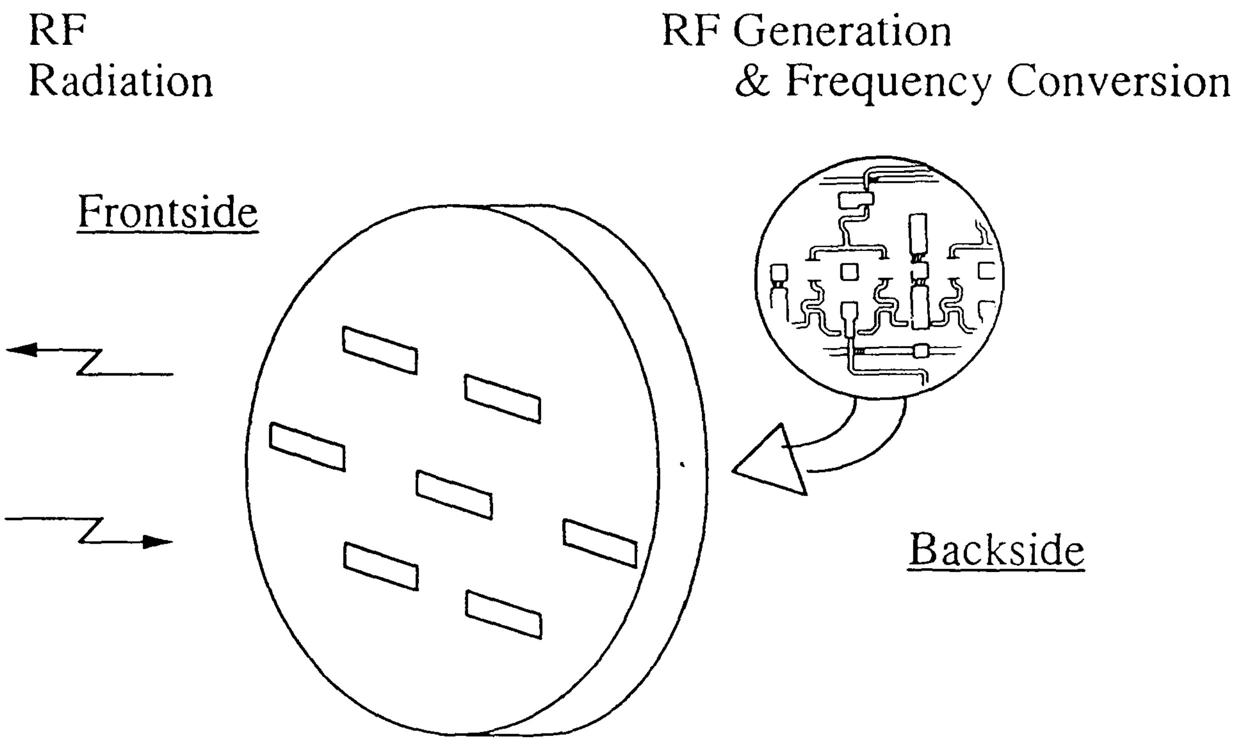
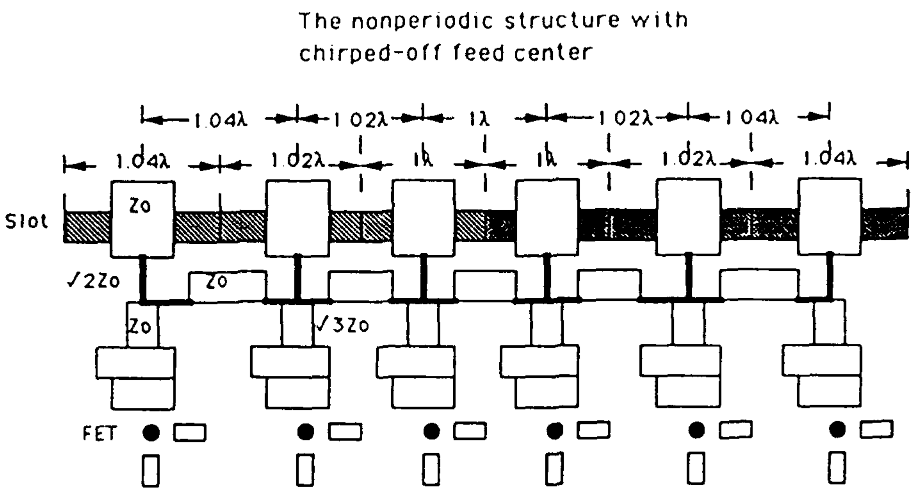


Fig.5 Slot based multilevel active antenna configurations



Circuit Structure

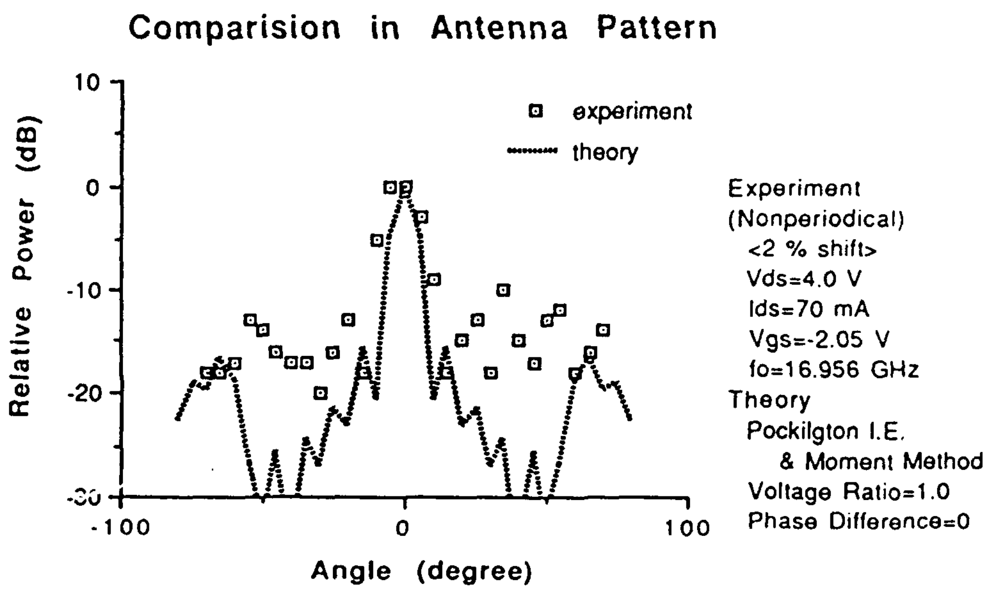


Fig.6 6-element nonuniform quasi-optical FET array range is almost twice of that for a periodic array, even though the radiation pattern is almost unchanged.

2.4 Distributed feedback type quasi-optical power combining oscillator [J10, J21, J28]

In this configuration, active devices such as Gunn diodes and FETs are placed periodically along a transmission line such as the microstrip line. The period is one guide wavelength at the desired frequency of oscillation. The operating principle is similar to the distributed feedback laser. At the frequency so chosen above, the periodic structure is in the leaky wave stop band. Hence, there exists a standing wave along the transmission line and at the same time radiative leakage takes place in the broadside direction. Therefore, all devices are locked to each other at this particular frequency and generate outputs which are constructively combined in free space.

This concept has also been extended to generate a second harmonic. Fig.7 is an example. The diodes are spaced at a half guide wavelength at the desired frequency of operation. Since this condition constitutes a surface stop band, all diodes are locked together to oscillate at this frequency. No radiative leakage occurs in principle. Due to the nonlinearity in the diodes, a second harmonic signal is generated in each diode. Hence, the interval of the devices is one-guide wavelength (if the dispersion of the line is ignored) so that the leaky wave stop band condition is realized for the second harmonic. In addition, in the present example, a microstrip patch resonant at the second harmonic is connected to each diode to facilitate efficient radiation of the second harmonic.

2.5 Nonlinear behavior [C33, C37]

Several efforts have been implemented to characterize the large signal behaviors of the multiple device oscillators due to the nonlinearity of the devices. Specifically, an iterative method based on the updated information of the active device presented to the passive side of the circuits The method was implemented either in the time domain or in the frequency domain. In the iterative process, a decellation factor was required. The choice of the value of such a parameter was studied and was a compromise. It was found that in some cases one of several devices becomes a master oscillator and the remainders become slaves and the contributions from individual devices to the total output power are not uniform. This effort is proposed to be continued in the renewal proposal by means of different numerical techniques.

2.6 Optical control of active antennas [C67, C71]

An effort for optical control of active antennas have been initiated. Tuning of the oscillation frequency of the slot based FET active antenna has been accomplished. One example is shown in Fig.8. In this scheme, the electrical characteristics of the FET are controlled by optical illumination so that the oscillation condition is modified. The radiation pattern of the antenna is essentially unchanged because the change of the frequency is rather small and the physical length of the antenna seen from free space did not change.

This optical control technique is expected to be important for future development of the quasi-optical technique. Due to the use of optical control signal, the circuit complexity on the chip can be reduced. In addition, optical control signals can be isolated completely from the electrical signals on the chip.

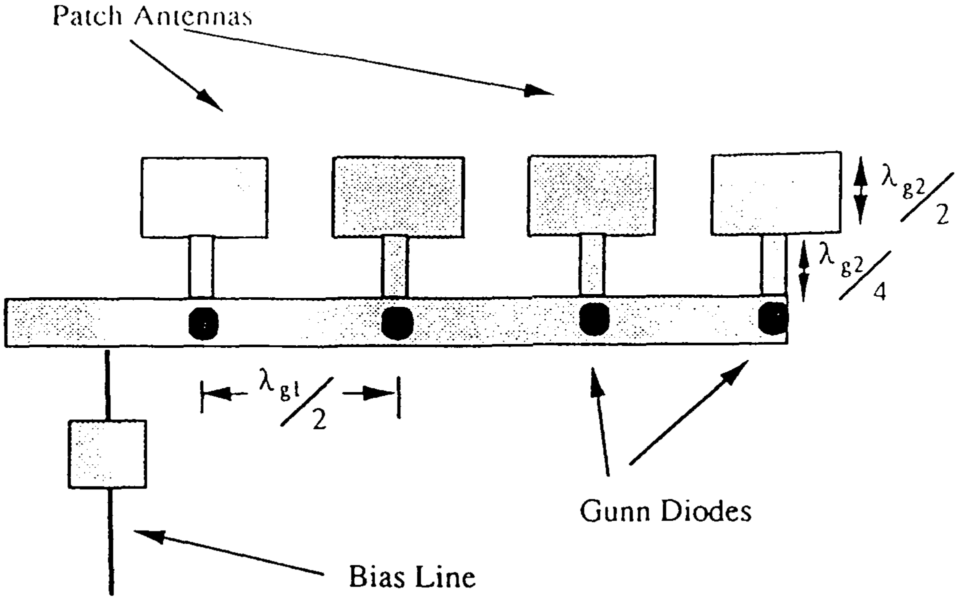
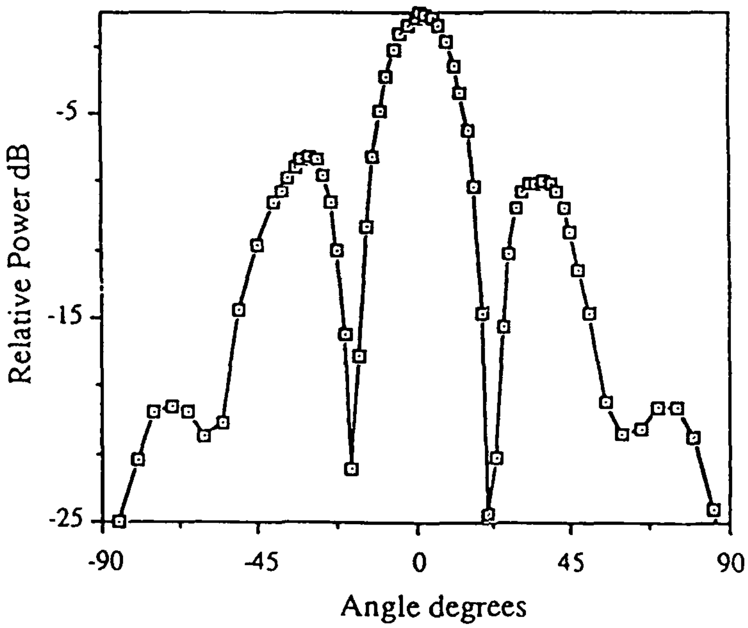


Diagram of a four diode spatial second harmonic power combiner

λ_{g1} is the guide wavelength at fundametal frequency

λ_{g2} is the guide wavelength at second harmonic

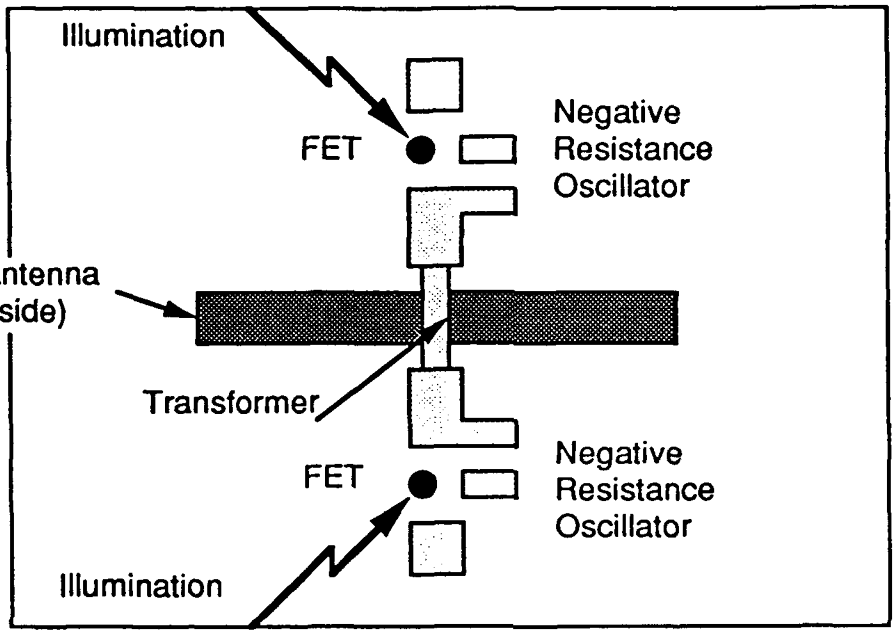
H-Plane Radiation Patteren



The H-plane radiation pattern of the four diode harminic combiner

Fig.7 Second harmonic power combiner

Active Integrated Antenna with Optically Controlled FET Oscillators



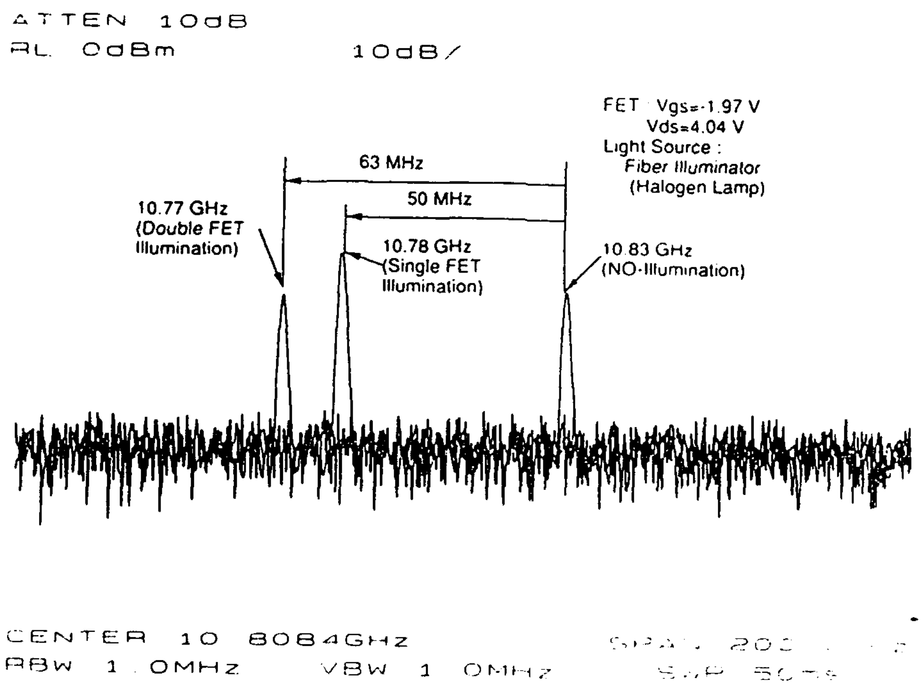


Fig.8 Optically controlled FET active antenna

3. ACTIVE TUNABLE FILTERS

In microwave and millimeter-wave monolithic integrated circuits, it is difficult to obtain a high Q resonator. This problem place a sever burden in the design of MMIC particularly for fabrication of filters and diplexers. To alleviate this situation, an innovative active bandpass filter has been proposed and studied [J9, J11]. This filter is particularly suitable for narrowband applications. In order to compensate a loss in the resonator circuit (a half wave open circuited microstrip resonator) of the bandpass filter, a negative resistance generated by an active device (typically FET or HEMT) is injected into the resonator through a transformer made of a quarter wave coupled section. This negative resistance cancel the resistance in the resonator which then can have an infinite unloaded Q. Therefore, the loss is eliminated and a sharp resonance curve can be obtained.

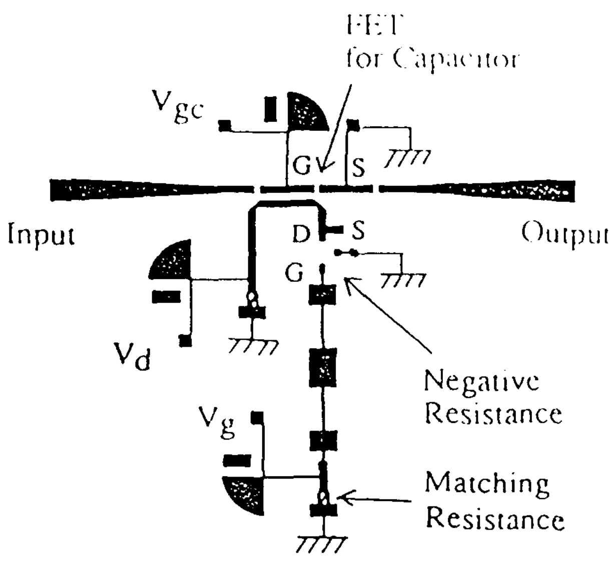
This active filter has been made tunable by inserting a variable capacitance element into the resonator [J14,J27]. Both varactors or FETs have been tested. The FET has two advantages. First, since the negative resistance is created by an FET, use of same type device reduces fabrication effort if a monolithic construction is attempted. Second, the FET is sensitive to optical illumination and hence the active filter can be tuned optically as well as electronically [C40]. Fig.9 shows an example of the active filter tunable electronically and optically.

4. TRAVELING WAVE TRANSISTORS

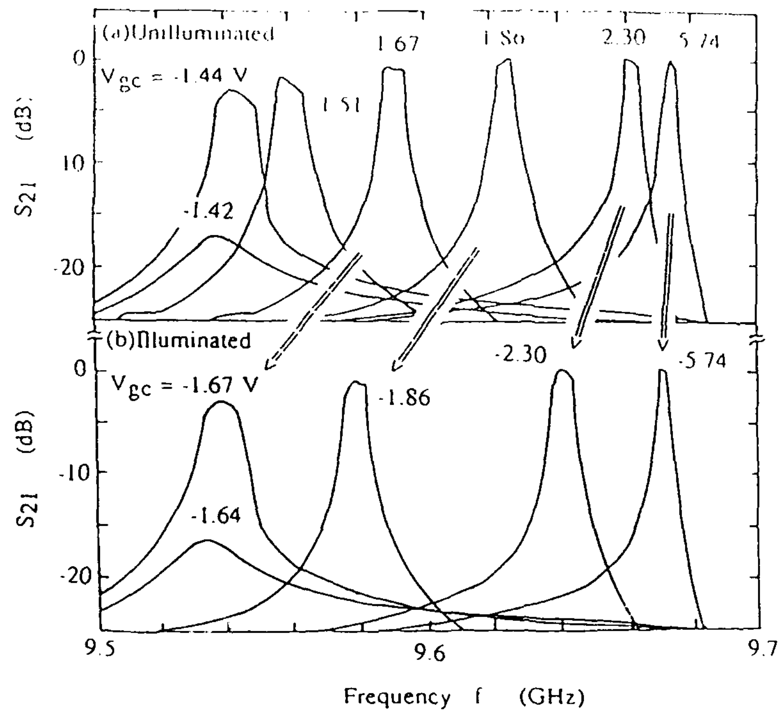
As the frequency is increased toward millimeter-waves, the width direction of the three-terminal devices can be a significant fraction of the wavelength and hence distributed effect needs to be incorporated in the design and characterization of the devices. On the other hand, it is conceivable to make use of the distributed effect. To study such phenomena, the traveling wave mode of the FETs along the electrode has been analyzed. The three terminals of the FETs have been considered to be a coupled transmission line with gain mechanism. An inverted gate structure was chosen since such a configuration is more suitable for phase velocity synchronization along the coupled lines. Based on the hydrodynamic model of the intrinsic transistor, a small signal characteristics of the device has been obtained. This characteristic was combined with the traveling wave analysis. The modal characteristics of this active coupled transmission lines have been studied for a number of termination conditions [J4, C5, C34].

5. SLOW WAVE STRUCTURES

In monolithic integrated circuits, it is necessary to reduce the size of passive components. At low microwave frequencies, this is typically accomplished by the use of lumped elements. At higher frequencies, lumped elements cannot be used. One way to alleviate the size problem is to use a slow wave structure. Since the physical length of such structure for a given electrical length, substantial size reduction of passive components is possible. This concept was demonstrated by means of crosstie overlay slow wave structures [C1, J13]. This structure consists of a planar transmission line such as coplanar waveguide (with a modification) which is loaded periodically with capacitance. The reduction of the guide wavelength as large as a factor of ten was realized. Several components have been fabricated and tested. They are Chebyshev transformers and



Circuit Pattern of Tunable Active Band-pass Filter



Performance of a Tunable Active Filter
(MTT Symposium, June 1991)

V_g (gate voltage of the negative resistance MESFET) :	0V
V_d (drain voltage of the negative resistance MESFET) :	2.01V
I_d (drain current of the negative resistance MESFET) :	100mA

Fig.9 Electronically and optically tunable active filter

frequency scanning leaky wave antennas. The latter is useful as an integrated antenna with a small size. Naturally, the beam is wide although it can be scanned. Such characteristics may find useful in personal communication.

The slow wave structure is also useful in designing a high speed optical modulator in which the phase velocity of the optical wave and the microwave modulating signal need to be synchronized [J3]. For a planar waveguide type modulator, the phase velocity of the microwave signal needs to be slowed down. The slow wave structure has been designed for this purpose. The device was fabricated at ETDL, Fort Monmouth. It was demonstrated that the velocity slow down was accomplished. Fig.10 shows the structure fabricated at ETDL.

6. ELECTROMAGNETIC CHARACTERIZATION OF DINSCONTINUIES IN PLANAR TRANSMISSION LINES

The spectral domain method has been extended to characterize the discontinuity in an open planar transmission line. One of the most comprehensive numerical analysis efforts based on the spectral domain method has been implemented. Both the transverse and longitudinal currents in the microstrip line or the transverse and longitudinal aperture fields in the coplanar or slot lines with two dimensional variations are correctly included. The program is capable of finding the radiation loss and surface wave excitations. The program has been applied to open, short, gap discontinuities in the microstrip, coplanar waveguide and modified coplanar waveguide [C28, C38].

A combination of the extended spectral domain for a thick conductor transmission line and a mode matching technique has been used for characterizing a number of discontinuities in a coplanar waveguide and a slot line [J18, C39, C41].

7. CHARACTERIZATIONS OF PLANAR TRANSMISSION LINES

An extension of the spectral domain method has been developed for characterizing a coplanar type transmission line with finitely thick conductors. It was found that the conductor thickness has a substantial effect on the propagation characteristics [J16].

A new type of transmission line called the stitch line (shown in Fig.11) has been proposed and analyzed. This is a vertically coupled microstrip line consisting of two strips and a ground plane. The top strip is placed in air directly above the superstrate on the center conductor of the microstrip line and is supported periodically with landing islands on the superstrate. This transmission line is a useful addition to monolithic microwave integrated circuits, particularly for a coupling structure. The structure has been analyzed including the attenuation constant. The numerical results were confirmed by the measurement carried out at Hughes Aircraft Company [C42].

A quasi-planar transmission line called the trapezoidal transmission line was analyzed by means of the boundary element method. This transmission line was proposed for higher millimeter-wave frequencies and intended to make use of a combined nature of microstrip line and a dielectric waveguide. The boundary element method was applied both under the quasi-static approximation [J17] and under a full-wave condition [J23, C68]. The results agreed well with the measured results as shown in Fig.12. It was found that due to its

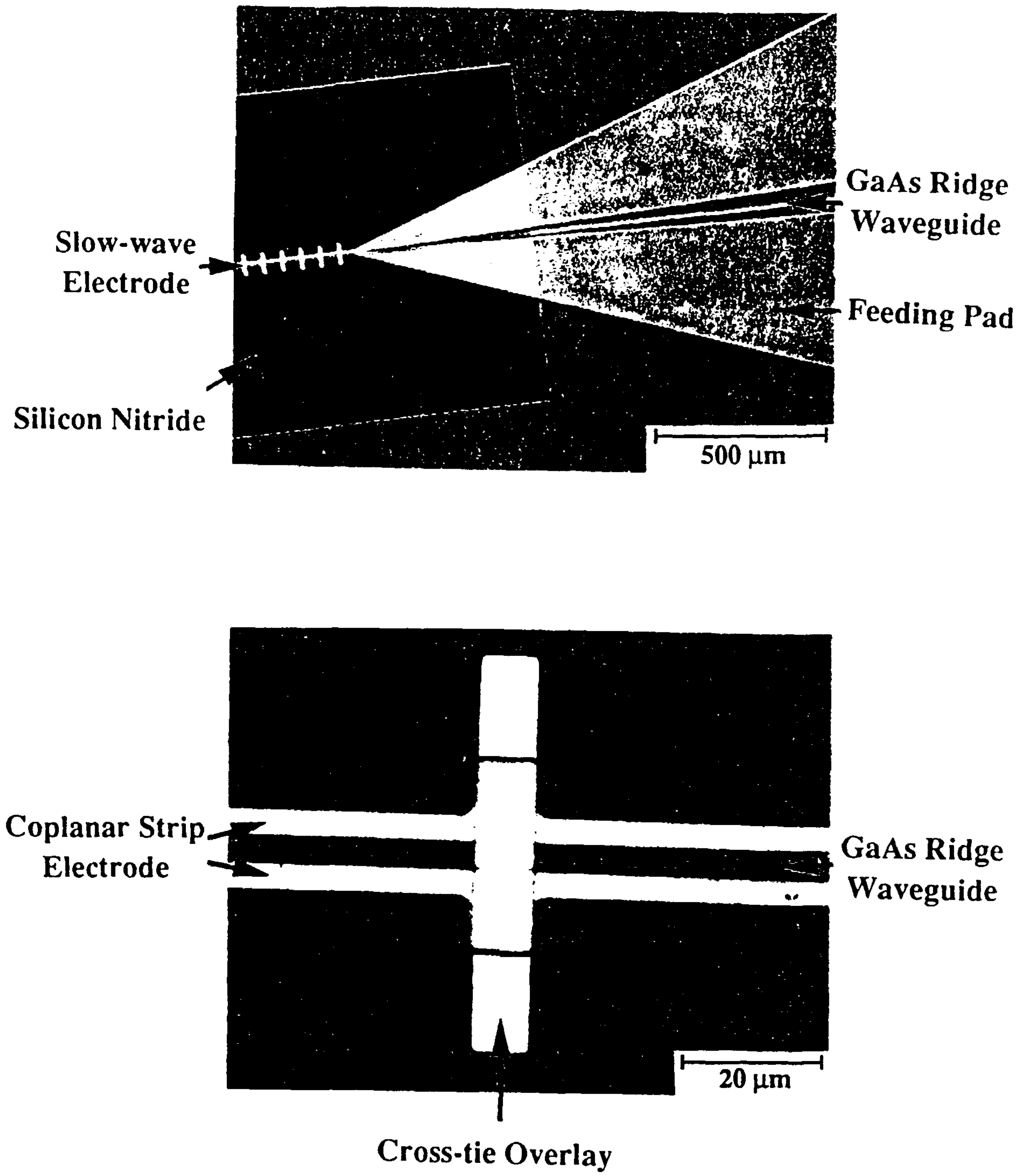
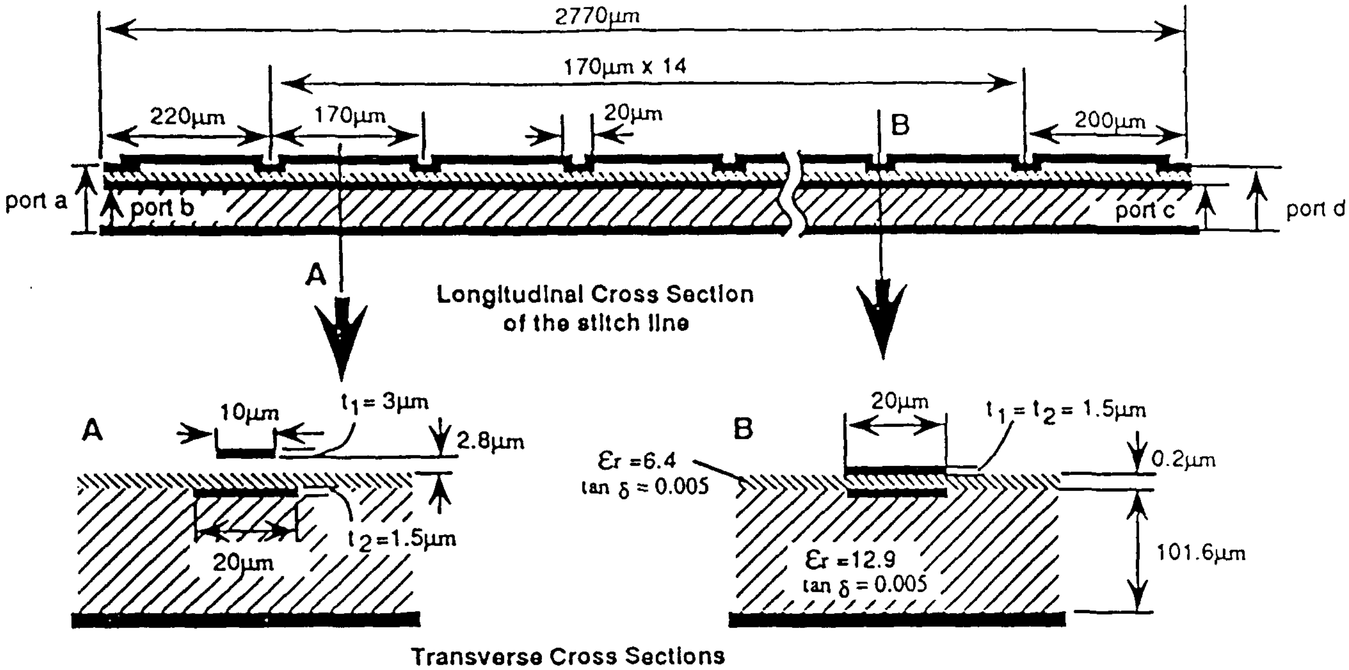
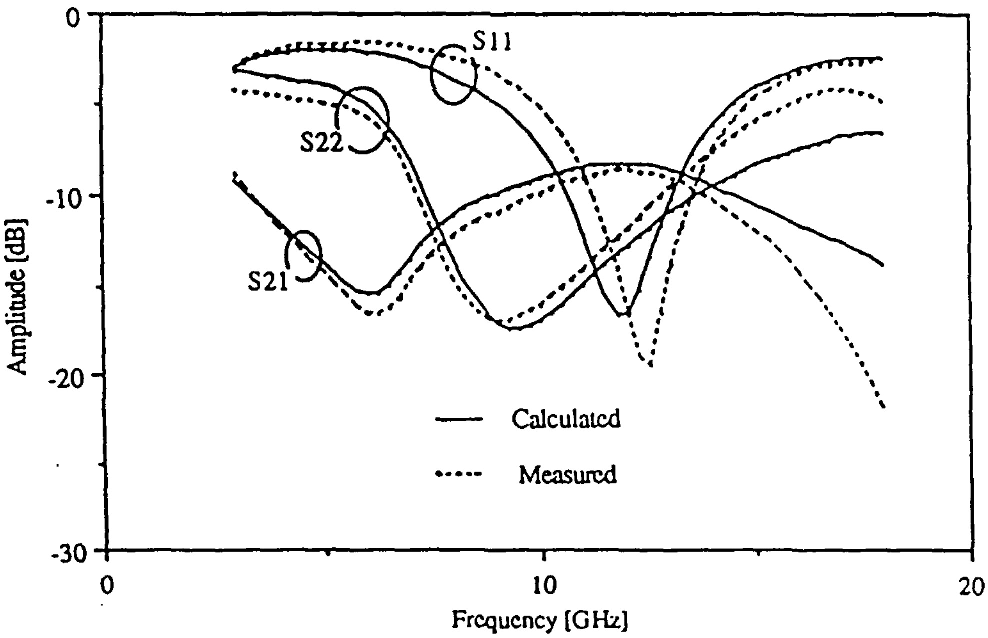


Fig.10 GaAs slow-wave optical modulator configuration



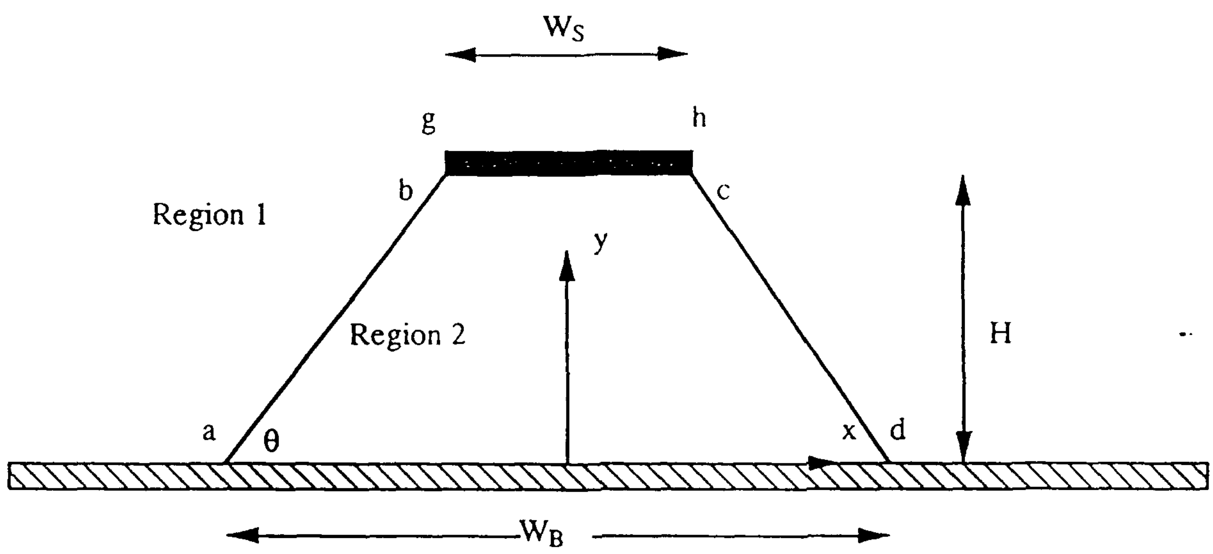
The measured circuit



The measured and calculated results

Fig.11 Stitch line

Boundary Element Analysis of a Trapezoidal Transmission Line (Quasi-Static)



Calculated Characteristic Impedance

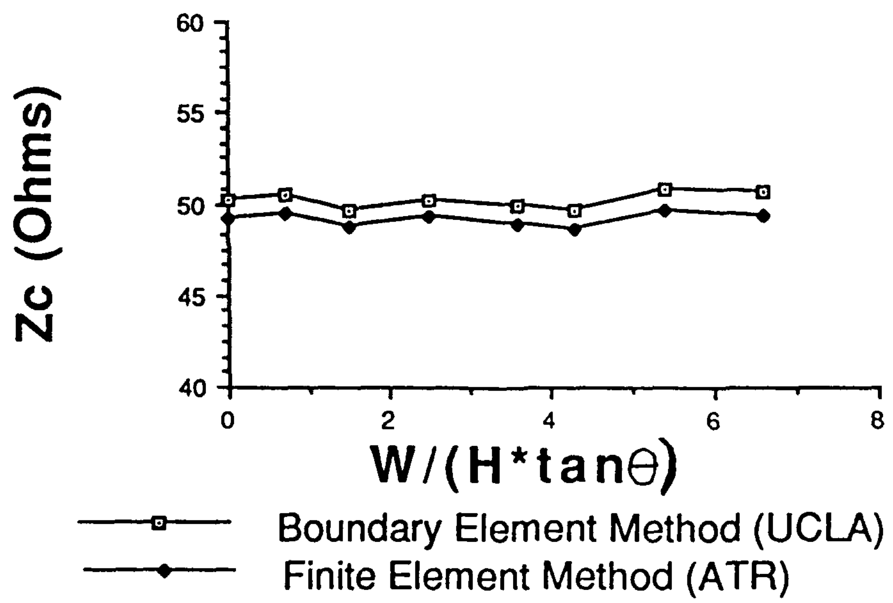


Fig.12 Trapezoidal transmission line

dimensions this transmission line retains the quasi-TEM nature up to an extremely high frequency.

8. CONCLUSIONS

In the above, the representative accomplishments under ARO support have been described. The pertinent references are cited from the List of Publications provided below. Also provided below is the List of Personnel and Students with Advanced Degrees awarded, where applicable.

LIST OF PUBLICATIONS UNDER SUPPORT BY DAAL03-88-K-0005
(April 1988 - December 1992)

Journal Publications

(J1). H.-Y. Lee and T. Itoh, "Wideband and low return loss coplanar strip feed using intermediate microstrip," Electronics Letters, Vol. 24, No. 19, pp. 1207-1208, Sept. 15, 1988.

(J2). T. Itoh, "Overview of quasi-planar transmission lines," (Invited) IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 2, pp. 275-280, Feb. 1989.

(J3). H.-Y. Lee and T. Itoh, "GaAs traveling-wave optical modulator using a modulated coplanar strip electrode with periodic cross-tie overlay," Int. J. Infrared and Millimeter Waves," Vol. 10, No. 3, pp. 321-335, March 1989.

(J4). S. El-Ghazaly and T. Itoh, "Travelling-wave inverted-gate microwave field-effect transistors, concept, analysis and potential," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 6, pp. 1027-1032, June 1989.

(J5). J. Birkeland and T. Itoh, "Planar FET oscillators using periodic microstrip patch antennas," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 8, pp. 1232-1236, Aug. 1989.

(J6). T. Itoh, "Recent progress of quasi-optical integrated microwave and millimeter wave circuits and components," Alta Frequenza, Vol. 58, No.5-6, pp. 507-515, Sept - Dec. 1989 (Invited Paper).

(J7). J. Birkeland and T. Itoh, "FET-based planar circuits for quasi-optical sources and transceivers," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 9, pp.1452-1459, Sept. 1989.

(J8). C.-Y. Chang and T. Itoh, "Narrow-band planar microwave active filter," Electronics Letters, Vol. 25, No. 18, pp. 1228-1229, Aug. 31, 1989.

(J9). K. S. Kong and T. Itoh, "Computer aided design of evanescent mode waveguide bandpass filter with non-touching E-plane fins," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No. 12, pp. 1998-2004, December 1989.

(J10). A. Mortazawi and T. Itoh, "A periodic planar Gunn diode power combining oscillator," IEEE Trans. Microwave Theory and Techniques, Vol. 38, No. 1, pp. 86-87, Jan. 1990.

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(C74) J. Lin, S. Kawasaki and T. Itoh, "Optical control of MESFETs for active filter and active antennas," MIOP '93, May 25-27, 1993, Sindelfingen, Germany.

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(C79) D.-C. Niu, T. Yoneyama and T. Itoh, "Measurement of NRD-guide leaky wave coupler in Ka band," 1993 IEEE MTT-S International Microwave Symposium, June 15 - 17, Atlanta, GA.

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(C84) J. Lin, S. Nogi and T. Itoh, "Mode switch in a two-element active array," 1993 IEEE AP-S International Symposium.

ADVANCED DEGREES AWARDED

Ph.D with Dissertation Titles (University of Texas)

(1) Samir El-Ghazaly, "Analysis and improvement of MM-wave GaAs MESFET's," May 1988.

(2) Vincent Hwang, "Planar integrated quasi-optical receivers," May 1988.

(3) T. H. Wang, "Confirmation of slow-waves in a crosstie overlay coplanar waveguide and its applications to band-reject gratings and reflectors," May 1988.

(4) J. Birkeland, "Planar integrated circuits for microwave transmission and reception," August 1989.

(5) H.-Y. Lee, "GaAs traveling-wave optical modulators using crosstie slow-wave electrodes and characterization of conductor loss in a wide range of field penetration," December 1989.

(6) C.-Y. Chang, "Microwave active filters based on coupled negative resistance method," May 1990.

(7) Y. D. Lin, "Analysis and applications of the crosstie-overlay slow-wave structure," May 1990.

(8) J. S. McLean, "The application of a deterministic spectral domain method to the analysis of planar circuit discontinuities on open substrates," May 1990.

(9) A. Mortazawi, "Microwave and millimeter-wave oscillators and planar power combining structures for QWITT and Gunn diodes," August 1990.

Ph.D (UCLA)

S. Kawasaki, expected March 1993.

M.S.with Thesis Titles (University of Texas)

S. S. Chang, "The boundary-integral method for planar microstrip circuits," December 1988.

K. S. Kong, "CAD algorithm for the evanescent mode waveguide bandpass filter with non-touching E-plane fins," December 1988.

M.S with Thesis Title (UCLA)

J. Lin, "Tunable active microwave bandpass filters using three-terminal MESFET varactors," December 1991.

RESEARCH PERSONNEL SUPPORTED OR PARTICIPATED

Faculty

T. Itoh, Principal Investigator, Professor (University of Texas and UCLA)
H. Ling, Assistant Professor/Associate Professor (University of Texas)

Research Assistants (fully or partially supported by ARO)

S. El-Ghazaly
V. Hwang
S. S. Chang
H.-Y. Lee
J. Birkeland
K. S. Kong
Y. D. Lin
J. McLean
A. Mortazawi
S. Kawasaki
B. Toland
J. Lin
O. Boric
Y. Liu

Research Students with Fellowship

T. H. Wang
C. Y. Chang
D. Niu

Post Doctoral Fellows

J. Birkeland
Y. Nikawa
T. Kitazawa

Visiting Scholars without cost to ARO

Y. Yamamoto
K. Kawasaki
J. B. Lim
T. Wakabayashi
S. Nogi
T. Yoneyama
T. Hirota