LOOKING BACK AT MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

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INTRODUCTION

A monolithic microwave integrated circuit (MMIC) is an active or passive microwave circuit formed in situ on a semiconductor substrate by a combination of deposition techniques including diffusion, evaporation, epitaxy, implantation and other means.

The monolithic microwave integrated circuit technology emerged with the following objectives: 1) low cost, 2) reliability and reproducibility, 3) small size and weight, 4) circuit design flexibility and multifunction capabilities, and 5) multioctave performance.

ORIGIN

PCB design

The microwave circuit integration concept started with the microwave printed circuit board approach. It used low dielectric constant insulating sheets, having interconnection patterns etched into a metallic coating on it, to accommodate circuit components. This insulating substrate acted as a transmission line medium reducing the wavelength. The main drawback of this design was that it provided little reduction in size and rather limited integration because of the inefficiency of the active elements that can be integrated.

Hybrid Integrated Circuit

The drawback of PCB design were addressed a decade later with the development of two port solid-state active elements and other higher dielectric constant substrate like sapphire and alumina. This method, hybrid integrated circuit, is been modified with time and is still very popular with designers.

MMIC

MMIC was started as a government funded program in 1964 with the aim of a transmitter receiver module for aircraft phased-array antenna based on silicon technology. The results were not as expected because the silicon is not able to maintain its insulating properties through the high-temperature diffusion processes in the formation of bipolar transistors. These lossy substrates were not acceptable for microwave circuitry. This program confirmed that the basic technology of circuit integration on a semiconductor chip developed for digital circuitry could be applied to analog microwave circuitry.

After few years the Three - five compound Gallium Arsenide showed promising results to solve the problem of lossy substrate. Due to the semi insulating state of Gallium Arsenide, this material is a good insulator and was used as the base material for MMICs. However, no planar GaAs-based two-port active device existed at the time.

After this, the progress took a rapid pace. The first GaAs MMIC came into being in 1968 using only diodes and another eight years to build X-band amplifier around the planar MEtal Schottky-gate Field Effect Transistor (MESFET) in GaAs MMIC.

In the 1980-1986 there was an enormous use of GaAs MMICs in circuit configurations over the entire frequency band up to 35GHz. Every kind of circuits were demonstrated from coupled amplifier to low noise amplifiers, signal generator, mixer and oscillators, direct broadcast satellite receiver, etc. The development of GaAS MESFET was an important factor for the growth of MMIC effort. The results served as proof of concept.

The report will be discussing the some of the simple circuit elements including, 1) switches, 2) oscillators, 3) power amplifiers, 4) broad-band amplifiers, and 5) transceivers and transmit/receive (T/R) modules.

SWITCH

The silicon-based-X-band switch, first demonstration of MMIC (1967), consists of a seven finger interdigitated surface-oriented p-i-n diode. Diode is used to switch between the transmitted and received signal to and from the antenna. The frequency of operation is around 8-9GHz with an isolation and insertion loss of 25-27dB and 1.5-2 dB respectively.

In 1980 Ayasli developed the GaAs version of T/R switch based on MESFET operated as a variable resistance with channel resistance being varied from infinite to zero depending on gate voltage. Schindler and Morris in 1986 extended the same principle to higher frequency using shorter-gate FETs and demonstrated a broadband switch. The main feature was the use of both series and shunt FETs.

The MESFET switch are technologically more advance than p-i-n diode switch and will have better applications in designing of monolithic transceivers and transmit/receive (T/R) modules for phased array radar systems.

OSCILLATORS

It was first introduced by van Tuyl in early 1981 as a signal-generating chip. The chip contains a switching modulator, local oscillator, RF phase splitter, a doubly balanced mixer, and IF amplifier interconnected. Five thin-film capacitors, twenty-nine MESFETS, eight diodes, and one implanted resistor were integrated monolithically. The local oscillator was resonated by an off chip inductor tuned over the 2.1–2.5 GHz range with an on-chip Schottky barrier junction capacitor.

This showed us one of the drawbacks of monolithic approach which is the unavailability of high-Q factor in circuit elements. This was due to the limited volume of energy storage in the resonating circuit elements printed on the chips.

Oscillator proposed by Schott, a year later, was a 8.8–10 GHz GaAs MESFET voltage-controlled oscillator with tuning varactors and inductors and boasted a 13% tuning range and 4mW power output.

In 1985 the first transistor-based oscillator with greater 100 GHz operating frequency was demonstrated. The circuit gave an output power of 0.1mW and is basis for monolithic Wband receiver front end.

AMPLIFIERS

The first monolithic GaAs format amplifier was reported in 1976, operating in the range of 7.0-11.7 GHz band and the gate length of 0.8 µ. The gain and noise figure at 10 GHz were 4.5 dB and 7.3 dB, respectively. This discovery lead to a series of innovation, a single-stage X-band power amplifier giving an output of 400 mW, a two-stage X-band amplifier, a four-FET power combiner.

The two technological innovations in design, namely the overlay or air-bridge technique used for interconnecting the various unit cells of the power MESFET and for crossing one conductor over another and the via hole technology for grounding the source straps and any other circuit element received wide acceptance from MMIC community.

These innovations were the driving block for the many more and better amplifiers to come.

A monolithic power amplifier with circuit elements imprinted entirely by selective ion implantation (planar process as it does not require mesa etching to isolate active areas of the chip) with the gain of 10 dB over the 5-9 GHz frequency range. A four-stage amplifier exhibiting a 27 dB gain at 9.0 GHz with a power output of one watt. The first millimetre-band MMIC amplifier in the form of a single-stage, parallel FET configuration, exhibiting a power gain of 5 dB and a power output of 60 mW at 44 GHz from two 150 µ periphery FETs with 0.3 µ gate lengths were utilized in the design.

In 1989, 5 W X-band heterojunction bipolar transistor (HBT)-based power amplifier was reported. Bipolar transistor as the active device added another degree of freedom in MMIC designs for power applications. They had high operating voltage and inherently high power density capability. Three years later the first GaAs-based complementary HBT monolithic amplifier was reported. Utilizing NPN and PNP transistors, fabricated by selective molecular beam epitaxy (MBE), in a push-pull configuration, an amplifier operating at dc to 2.5 GHz band (3 dB) with a saturated power output of 7.4 dBm was achieved. This helped to reach higher power efficiencies in push-pull amplifiers without the need for complex transformer circuits.

BROADBAND AMPLIFIERS

There are have various methods for broadband applications. One of the traditional methods is the use of shunt-resistive loading to equalize the gain over a wide band. Another is the application of negative feedback between the output and input circuits. Another approach for multi octave bandwidths is the distributed or traveling-wave amplifier which is the combination of the above two. In this approach, the bandwidth limiting input and output capacitances associated with the active device are incorporated into artificial (lumped element) or distributed transmission lines where they are rendered less harmful. The two transmission lines are coupled by the transconductance of the active devices distributed periodically between them. Also Using InP substrate, rather than GaAs, and replacing microstrip lines (MS) with coplanar waveguides (CPW), achieved a 5.0 dB gain extending over a 5 GHz to 100 GHz band with a seven-section amplifier. This performance was made possible by the use of higher frequency 0.1μ gate length InGaAs-InAlAs HEMTs. In 1989, the first octave-band power amplifier with output in excess of 10W over the S/C band 3–6 GHz. was reported. The next amplifier announced was a 1 W 6–18 GHz GaAs-based power module in 1990 consisting of two channels, each composed of a traveling-wave pre-amp driving a pair of two-stage reactively matched power amplifiers. The next amplifier in the exhibit is unique in that it employs a series of HBT amplifier stages interconnected in a distributed matrix configuration. , having 9.5 dB nominal gain over the 3 dB bandwidth extending to 24 GHz.

RECEIVERS AND TRANSCEIVERS

MMIC has been mostly used in receiver and transceiver chips. The first chip possessing the basic element of receiver which converted the input signals in the 70–90 GHz band to a 2.5 GHz IF output signal was reported in 1968. A 29 GHz band receiver chip featuring a MESFET IF pre-amplifier stage was reported after 12 years using 31 GHz oscillator as an external source.

In 1984, an integrated receiver chip consisting of a 12 GHz low noise amplifier, filter, mixer, local oscillator, and IF amplifier was designed for the emerging, and potentially large-volume, commercial direct broadcast satellite (DBS) market. An off-chip dielectric cavity was used to stabilize the local oscillator. The conversion gain was 25 dB with a 4.5 dB noise figure.

MMICs was also used is in transmit/receive (T/R) modules for electronically scanned radar antennas giving small size and reliability the prime importance. The first monolithically based T/R module consisted of 11 separate GaAs MMICs interconnected on a metallized alumina substrate mounted in a metal base with 50-ohm terminations. The X-band module contained a transmitter or power amplifier section, a low-noise receiver section, SPDT switches of the nature described earlier, and an electronically controlled 4-b phase shifter. The phase shifting elements employed dual-gate MESFETs and exhibited some gain. Two additional switches were required because of the unilateral nature of the phase-shifter. In 1985, T/R module finally appeared but with two changes from the earlier version. Aside from being on a single chip, the active phase-shifter was replaced by a passive one, thus eliminating two switches, and a fifth bit was added to the phase shifter.

CONCLUSION

There have been a great number of remarkable achievements in GaAs MMIC field in the two decade plus period from 1960s to 1980s. MMICs are now part of most modern radars, communication systems and hand held devices, and current trends show that this technology will continue to play an important role in radar and communication systems in the foreseeable future.