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GaAs MONOLITHIC INTEGRATED CIRCUITS FOR DBS RECEPTION

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Abstract. The goal of this paper is to present the application of the monolithic microwave integrated circuits (MMICs) in the direct broadcast satellite (DBS) receivers. A brief history of MMICs in this area, availability and future trends are outlined. Typical MMICs for individual functions of low-noise down converter as well as fully monolithic multifunction down converter chips are considered.

Key words: Microwave integrate circuit, WARC, DBS system, IF amplifier, mixer, MESFET, local oscillator, down converter.

1. Introduction

Television broadcast systems via powerful direct broadcast satellites break (DBS) are currently in use in various countries. A formal beginning of DBS era was in 1977 when the World Administrative Radio Conference (WARC) allotted frequency bands for medium and high power DBS systems.

Direct-to-home (DTH) systems are entered into operation in the mid 1980's. The first Ku-band DBS direct-to-home television began on May 12, 1984, in Japan, by launching BS2A satellite. On July 4, 1987 a full 24-hour service for Japanese consumers started with the BS2B satellite [1], and in 1991 the third satellite, BS3B, was launched. The year 1988, when the first ASTRA satellite was launched, is taken as European DTH start [2]. Currently, there are many European true DBS satellites as Marco Polo, Olympus, TDF, TVsat 2, etc., with several tens direct-to-home TV channels.

Success of DBS systems is in close ties with the availability of low-noise block down converters for the front ends of home receivers, in large quantities and at an acceptable price. In view of the potential of large-scale

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production and low cost, the GaAs MMICs are the most serious candidate for this application. On the other hand, the DBS market as the largest civil market is very attractive for MMIC manufacturers, thus a great attention is paid to the development of this circuits.

2. MMIC Fundamentals

The gallium arsenide monolithic microwave integrated circuits (GaAs MMICs) are integrated circuits which incorporate various active and passive components on a single GaAs chip [3]-[9]. Such chips perform individually the microwave functions as amplification, mixing, switching, phase shifting, filtering, etc., or combine two or more of these functions ("multi- function" chips). MMICs are a logical development of hybrid microwave integrated circuits (MICs), in which the planar transmission lines are printed on a dielectric substrate and active and passive discrete components are then attached.

The basic active element in MMICs is GaAs MEtal-Semiconductor Field-Effect Transistor (MESFET). MESFET has become one of the most highly utilized devices in the microwave industry. Over the range from 1 GHz to millimeter-wave frequencies, the MESFET offers several advantages over competing device technologies. Compared with silicon bipolar transistor, GaAs MESFET has lower noise figure, higher gain and can operate at a higher maximum frequency. Among the novel types of transistors, the High Electron Mobility Transistor (HEMT) seems most attractive for application to MMICs, because of its extremely low noise [3], [10].

Diode-based MMICs fulfill very important functions as mixing, phase shifting, etc. MMIC technology supports Schottky and PIN diodes only [3].

The choice of transmissive media in the design of MMIC is similar to that implemented in hybrid circuits. Today, the microstrip line approach is the most popular. Inductors take one of three forms: a microstrip section (often meandered), a single loop, or a spiral inductor. Spiral inductors have circular, square, or octagonal shape. The most popular MMIC capacitors are interdigitated capacitor and metal-insulator-metal (MIM) capacitor. Resistors may be constructed from either thin metal films such as NiCr, or from the GaAs layer itself.

MMICs offer considerable advantages over the MICs [3]-[9]. Perhaps the most important feature of MMICs is the ability of low cost in high-volume production. Further, these circuits have extremely small size and weight, broader frequency band performance, improved reliability and reproducibility, etc. However, some difficulties should be pointed. Because monolithic circuits cannot be experimentally modified, their calculated performance must be extremely accurate. MMIC design required very special strategies that combine the best modeling techniques with a statistically based yield analysis. For that purpose, a new generation of CAD software is needed. Further difficulties are connected with the high initial equipment cost, immature technology, etc.

In the selection of technology, the cost is one of important factors. The following origins of total MMIC cost can be pointed [7]: Design rules cost is high, since each foundry has its own set of design rules corresponding to its (usually unique) complex fabrication process. Mask set cost is also high because MMIC require a mask set containing up to fourteen photomasks (while MIC require only two photomasks). Further, fabrication cost per a wafer is significant, because MMICs are fabricated by a very expensive multistep process. Obviously, total cost per chip is a function of chips number because a high percentage of cost is constant for any volume. The comparison of the cost per circuit between MMIC and MIC should be made as a function of volume. Approximately, if more than 500 circuits are to be manufactured, MMICs have a clear economic advantage. Besides, many other factors can be significant in the selection of monolithic or hybrid technology.

3. Individual MMICs for DBS Low–noise Block Down Converters

A DBS receiver consists of antenna, low-noise block down converter (receiver front-end) and indoor unit. Block diagram of a typical DBS down converter is presented in Fig. 1.

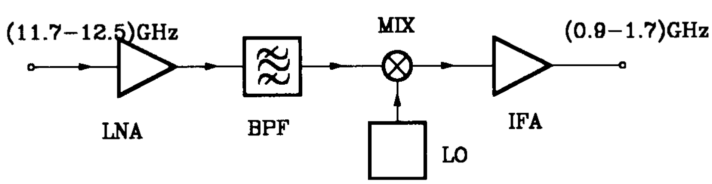


Fig. 1. Block diagram of a typical DBS down converter.

The low-noise block down converter (LNB) is composed of a GaAs FET low-noise amplifier (LNA), a band-pass filter (BPF), a mixer (MIX), an intermediate frequency amplifier (IFA) and a local oscillator (LO). Functionally, a LNB converts an 11.7-12.5 GHz input signal to a 0.9-1.7 GHz output signal. The individual circuits can be designed and fabricated separately in the hybrid or monolithic form, and then connected to a more complex system. At the highest level of integration, fully monolithic LNBs are developed [24], [25], [26].

3.1. Monolithic low–noise amplifiers

There have been many attempts to develop a MMIC low noise amplifier (LNA) suitable for LNB applications.

The basic goal in the DBS LNA design is a low noise figure. The upper limit for noise factor depends of several factors and cannot be strictly defined. For instance, usual requirements are 1-2 dB [1], [11] or better.

Design goals for the gain of a LNA should be given taking into account two factors: A large gain makes the total noise performance of the LNB less sensitive to the noise figure of the MIXER and IFA. On the other hand, too high gain degrades the intermodulation characteristics of the LNB.

The other demands are related to cost, miniaturization, good reproducibility, etc.

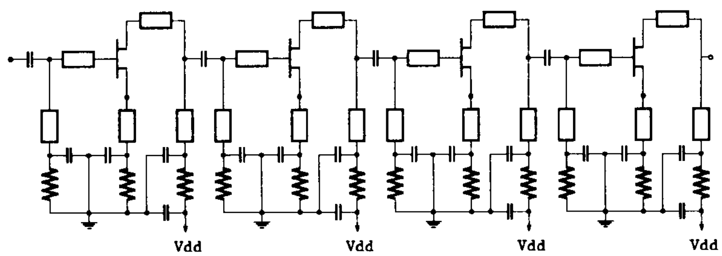
Until now, two types of device approaches have primarily been reported for MMIC LNAs: one is a GaAs ion-implantation MESFET and the other is a AlGaAs/GaAs HEMT. From the point of cost, ion-implantation MESFETs are favorable. On the other hand, HEMTs have an advantage in excellent low-noise performance. Therefore, research and development in both kinds of technology have increased over the last years.

First MMIC low-noise amplifiers are developed for much than ten years. Some of these early LNAs will be mentioned here. In [12], a three-stage LNA was presented. The total chip size was 1.5 x 3.0 mm. A noise figure less than 3.4 dB and a gain greater than 19.5 dB were obtained from 11.7 to 12.2 GHz. A two-stage LNA was developed by T.Sugiura et al. [13]. This amplifier has less than a 2.8 dB noise figure with more than 16 dB associated gain from 11.7 to 12.5 GHz, and the chip size was 1.5 x 0.9 mm. In [14], single and two-stage amplifiers are described. The measured noise figure of the single stage amplifier was 2.2 dB with an associated gain of 10.9 dB at 12 GHz. At the same frequency, the two-stage amplifiers have achieved 2.5 dB noise figure with 22.0 dB associated gain. Obviously, these early LNAs have had relatively high noise factors from the practical point of view.

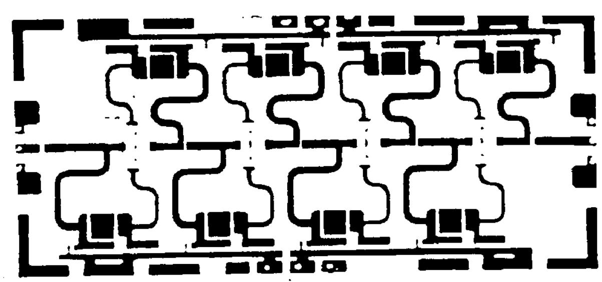
A very successful work was presented by Ayaki et al. [15] in 1989, where a four-stage LNA MMIC based on MESFET with 1.76 dB noise figure and 28 dB of gain was reported.

Very recently (Oct.1992), a group of Japanese authors reported of a MMIC LNA, based on pulse-doped MESFET, fabricated by a modern technology (organo-metallic vapor phase epitaxy) [11]. A four-stage amplifier has been designed and fabricated. The size of this MMIC chip was 4.5 x 2.2 mm. The measured noise figure was about 1.6 dB and gain about 24 dB across the band from 11.7 to 12 GHz. The circuit diagram and a photomicrograph of chip are shown in Figs. 2(a) and 2(b), respectively.

However, it should be pointed [1], that the best way to meet very stringent noise factor requirements at the current level of technology, is the use of discrete HEMTs because of their superior noise figure performance.



(a)



(b)

Fig. 2. Four-stage MMIC LNA
(a) Circuit diagram.
(b) Photomicrograph of the chip.

3.2. Monolithic mixer

In the research and development of MMIC mixers both diode and MESFET are used as a mixing device. Dual gate MESFET mixer seams to be most attractive option, because that topology, in comparison with other mixer topologies, provides good LO to RF isolation without the use of large filtering networks.

One of the earliest works in this area was a dual gate MESFET mixer reported in [16] (1982). The size of the chip was 2.4 x 1.4 mm. Noise figure of 6.5 dB has been measured, associated with maximum conversion gain of 2 dB.

The design considerations and microwave performances for a GaAs monolithic mixer for use in DBS receivers, based on a dual gate MESFET also, have been described in [17] (1983). Chip size was 0.96 x 1.26 mm. The mixer provided 2.9 ± 0.4 dB conversion gain with 12.3 ± 0.3 dB single side band noise figure.

A much better result was reported by Michels et al. in 1990 [18]. The dual-gate MESFET was used. The circuit design was performed by time-domain nonlinear circuit analysis program SPICE. A special attention is paid to the noise analysis. In the design of matching filter network and biasing network, spiral inductors, as a critical part, were characterized and modelled very carefully. All the components of the mixer, including biasing circuitry, RF, LO and IF matching networks, as well as IF noise filter, were implemented monolithically into a 0.63 x 0.76 mm area. The mixer had a conversion gain of 5.5 dB and a single-sideband noise figure of 8.5 dB.

A recent MMIC mixer solution is presented in [11] (1992). This mixer is based on a single gate MESFET and corresponding circuit diagram is shown in Fig. 3(a). The chip size, whose photomicrograph is presented in Fig. 3(b), is 2.9×2.4 mm. A conversion gain of more than 2 dB from 11.7 to 12 GHz is obtained.

3.3. Local oscillator

Many papers have been published on the MMIC oscillators for DBS applications [11], [12], [19], [20], [21], [22], etc. The oscillators can be stabilized by a dielectric resonator (DRO) which is outside of chip, or by a varactor diode (VCO) which can be outside of chip or integrated on chip. It can be pointed that the dielectric resonator oscillator (DRO) is more popular for down conversion in DBS systems, because of its better performance in view of temperature stability, size, cost etc.

For instance, a dielectric resonator oscillator with a center oscillation frequency of 10.67 GHz is presented in [12] (1983). The output power was 10.5 dBm, the frequency stability was about 0.2 MHz/V and the temperature stability was 1.5 MHz over a temperature range from -40 to 80°C. The chip area was 1.5 x 1.5 mm.

A more recently developed DRO (presented in [11], 1992) achieved an output power of 9 dBm at 10.678 GHz, frequency stability of about 0.1

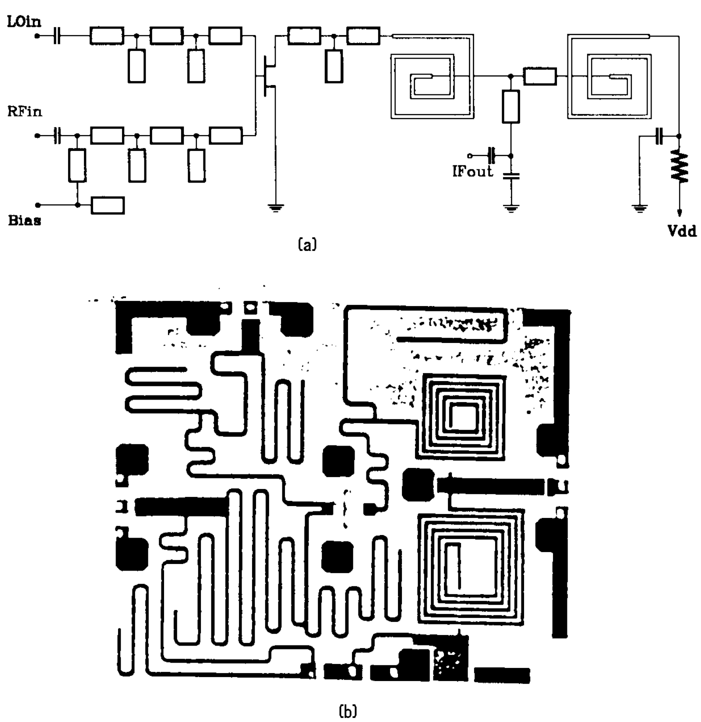


Fig. 3. A MMIC mixer for DBS applications.
(a) Circuit diagram.
(b) Photomicrograph of the chip.

MHz/V and output power stability of about 0.1 dB/V. The chip dimensions were 1.9 x 1.6 mm.

3.4. IF amplifier

After the down conversion, the IF range is 0.9-1.7 GHz. At this frequency range both GaAs and silicon bipolar devices can be used. Silicon monolithic IF amplifiers have been available commercially from NEC and Avantec since 1983. Contemporary, several GaAs IFA were reported.

A three-stage GaAs monolithic IF amplifier chip (1.5 x 1.5 mm) was evaluated by S.Hori et all. [12]. A noise figure less than 3.9 dB and a gain 23.5 ± 0.1dB were obtained. Since an IF amplifier gain of greater than 40 dB was required to operate the outdoor unit, two IFA chips were cascaded in the package.

In [11] an IFA with similar performances is presented. A monolithic three-stage amplifier had the size 1.9 x 1.2 mm, and a gain of 25 dB. Two IFA chips are connected showing a gain of 45 dB.

4. Integrated DBS LNB Down Converters

Some of individual LNB circuits can be realized together, in a monolithic form. In [23], a complex GaAs MMIC for a DBS receiver front-end is described. The chip includes a local oscillator, a selective buffer amplifier and a mixer. A 12 GHz LNA and a 1 GHz IFA are not integrated into that circuit and can be connected in a hybrid way.

In 1990, Wallace et al. [25] reported the first development of an economical, fully integrated DBS LNB down converter. The chip comprised a low-noise amplifier, an image band-pass filter (BPF), an IF amplifier and a dielectric resonator oscillator. It replaces about 50 discrete components now typically used in an outdoor DBS receiver. The chip was designed to minimize chip area and allow use inexpensive foundry processes. To minimize cost, this chip was designed without through-substrate vias. Spiral inductors and MIM capacitors were used for matching circuits and filters. MESFETs were used for amplifier, mixer and oscillator functions. A low-cost hermetic package was used, and only an external dielectric resonator and +6V and -5V bias were required for operation. The GaAs MMIC chip area was 2.1 mm^2. Typical noise figure was 5 dB with 36 dB conversion gain.

Very recently [27], the design, fabrication and measured performance of a GaAs monolithic image rejection down converter have been described. The chip includes a LNA, an image rejection mixer (IRM) and an IFA, but a local oscillator is off chip. The image rejection mixer includes a band-pass filter. The emphasis in the design of this filter is on size reduction as well as on compatibility with MMIC fabrication technologies. The total chip size was 2.8 x 2.8 mm. A conversion gain of 37 dB and a noise figure of less than 3.5 dB is obtained. The authors emphasize that the current dissipation of this down converter is at least one-half of that of commercially available hybrid circuit counterparts.

5. Commercial Availability of GaAs DBS MMICs

Commercial GaAs MMICs for DBS reception are available from several companies as NEC, Hitachi, Mitsubishi, Fujitsu, Avantec, Anadigics, etc. For the illustration, NEC's GaAs MMIC product offerings for outdoor receiver units with the specifications are listed in Table 1.

Anadigics [1], [4] offers fully integrated down converter MMICs for LNB applications. The MMIC incorporates LNA, band pass filter (BPF), mixer,

Table 1. List of NEC's GaAs MMICs for LNB applications

Function	Specification
LNA–1	$G_a = 16$ dB, NF=2.2 dB
LNA–2	$G_a = 16$ dB, NF=3 dB
MIX	$L_c = 6$ dB
LO	$P_o = 15$ mW, $F_o = 10.678$ GHz44
IFA	$G_a = 16$ dB, NF=4 dB

low pass filter (LPF), LO and IFA functions on a single GaAs chip. The four device types are commercially available for specific DBS bands. Conversion gain for these devices is 36 dB and noise figure is 5 dB.

In Europe, several companies as Thomson, Philips, GEC-Plessey and Siemens are also active in the development of MMICs for DBS.

6. Future Trends

A significant growth of the DBS market can be noticed. At the beginning of 1992 there were more than 4 million Ku-band DBS receivers in service in Europe and Japan [2]. It is estimated that by 1994 this number will be 20 million. According to some forecasts, a potential future market of several hundred million receivers is estimated [3]. (over 100 million in Europe [4]).

Future progress in DBS area will be driven by several factors. The launch of new satellites will provide additional channels of programming, using some of them for high–definition television (HDTV). Because of the growing needs, the use of new frequency bands is already certain. For instance, the frequency band 22.5-23.0 GHz was allotted to ITU regions 2 and 3 for direct-to-home satellite broadcast services. The band is expected to be used for new media services such as integrated services of digital broadcasting (ISDB) and digital high- definition television (HDTV) in the future. A simple, high performance 22 GHz band down converter based on MMICs is already developed by Japanese authors [26].

High quality receivers, available at relatively low prices will be an essential part of DBS progress. In this area, MMICs will play certainly a significant role. Currently, although individual MMICs for down conversion and some fully integrated LNBs are commercially available, it can be concluded that this circuits are still under development. Namely, it is obvious that a high level of functionality and circuit size minimization are achieved at the expense of relatively high noise figure, in contrast to state-of-the art hybrid LNBs. To meet the stringent design requirements for noise performance, further research efforts will probably direct to favor a solution that includes HEMT technology rather than the fully MESFET option. Future MMICs for LNB functions presumably will incorporate more and more functionality on a single chip and will be available in inexpensive, easy to use plastic, surface mountable packages.

6. Conclusion

In the last decade, a significant progress is achieved in the development of low-noise down converters for the front-ends of DBS home receivers. Monolithic microwave integrated circuits (MMICs) are very convenient for this application, in view of possibility of large–volume production at a low cost, extremely small size and good reliability and reproducibility. Taking into account a grand potential market for DBS receivers, it is estimated that low-cost, miniature MMIC converters will play a dominant role in the future.

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