K-Band and Millimeter-Wave MMICs for Emerging Commercial Wireless Applications

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***Abstract*—The recent K-band monolithic-microwave integrated-circuit (MMIC) technologies for the local multipoint distribution service systems and novel MMIC technologies for potential low-cost millimeter-wave MMICs are presented in this paper via a review of Fujitsu Quantum Devices Limited technology. The devices being demonstrated are a 23–26-GHz 2-W power amplifier module with a broad-band driver amplifier, a 19–33-GHz miniature low-noise amplifier, a frequency multiplier by four for K-band local oscillators, a flip-chip MMIC module for radar application, and three-dimensional MMIC image-rejection harmonic mixers. Through these devices, the recent trend of design and fabrication methodologies for the K-band and millimeter-wave devices will be described.**

***Index Terms*—Commercial wireless, flip-chip, K-band, low-noise amplifier, millimeter wave, MMIC, pHEMT, power amplifier, three-dimensional MMIC, voltage-controlled oscillator.**

I. Introduction

Emerging commercial wireless applications at quasi-millimeter- and millimeter-wave frequencies have significantly increased the activity in a high-yield production of K-band power amplifiers (PAs) and low-noise amplifiers (LNAs) [1]. The applications include local multipoint distribution service (LMDS), fixed satellite, and digital point-to-point radio services. Millimeter-wave MMICs above 60 GHz have also been developed aggressively for future commercial applications.

In GaAs pseudomorphic high electron-mobility transistor (pHEMT) power monolithic-microwave integrated-circuit (MMIC) technology has recently made great strides at K-band frequencies and at an output power level of 2 W, while there still exist some issues on assembly, reliability, cost, and shipment. An output power level of 4 W is currently desired for improvement of the wireless services. LNAs has also been developed and commercialized using 0.1–0.15-μm-gate pHEMTs and the level of noise figure is less than 2 dB over the LMDS band (i.e., 22–42 GHz). However, the gain density is not high enough due to large die size, which results in cost increase. For the commercial wireless services, PAs, LNAs, and all other MMIC components are strongly required to be low cost, easy to use, and reliable on the basis of mass production, as well as to be broad band. This paper demonstrates the latest PA and LNA MMICs for a broad-band wireless infrastructure. A multiplier ($\times$4) MMIC is also described because it can be a key component of local oscillators for the communication systems.

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The millimeter-wave frequencies are expected for future higher speed and short-distance wireless services and also used for current automotive radar application. An important issue there is low-cost assembly and MMIC fabrication. Both the multichip-module assembly and the single-chip integration are considered to be the potential solutions. Each of these technologies is effective if some breakthroughs have been done. Technologies in the author's sight are flip-chip MMIC technology using batch-processed tiny gold pillars and three-dimensional MMIC (3-D MMIC) technology using a polyimide or benzocyclobutene (BCB) multilayer structure across the wafer surface. When these technologies become matured, and combined with each other if necessary, functional modules can be produced at a low cost for both quasi-millimeter- and millimeter-wave applications.

II. K-Band MMIC Technologies

The LMDS bands are allocated over a frequency range from 22 to 42 GHz in the world. The point-to-point systems also utilize similar frequencies. The U.S. licenses the 24-, 28-31-, and 38–40-GHz bands, Japan licenses the 22-, 26-, and 38-GHz bands, Germany licenses the 26- and 40–42-GHz bands, Canada licenses the 22- and 26–29-GHz bands, and so on. The region between 32–38 GHz is not announced for the LMDS use. This planned frequency bands accelerated commercialization of K-band MMICs. The first half of this section will focus on the latest power and LNA MMICs for the broad-band wireless infrastructure. The second half will show a multiplier MMIC for a low-cost voltage-controlled oscillator (VCO) solution. These counterparts are to be broad band for lower cost. Down- and up-converters are also to be broad band, however, the designs strongly depend on each system integration concept.

A. PA MMIC

The latest PA module in a package for the 23–26-GHz application [2] is shown in Fig. 1, where a driver amplifier (DA) MMIC for the first stage and a 2-W PA MMIC for the second stage are die-bonded with associated interconnect board and chip capacitors. The DA and PA are $2.6 \times 1.4 \times 0.07$ mm and $3.8 \times 3.65 \times 0.028$ mm in size. This packaged form is very easy to use and reliable for customers rather than chip form. This meets the recent market requirement. The test fixture indicates an easy test of the PAs by both the customers and providers.

To achieve the PA performance, we newly developed a power pHEMT, as shown in Fig. 2. This power pHEMT is composed of a buffer layer, an n-AlGaAs/I-InGaAs/n-AlGaAs double heterostructure, an n-AlGaAs Shottky layer, and an n-GaAs cap

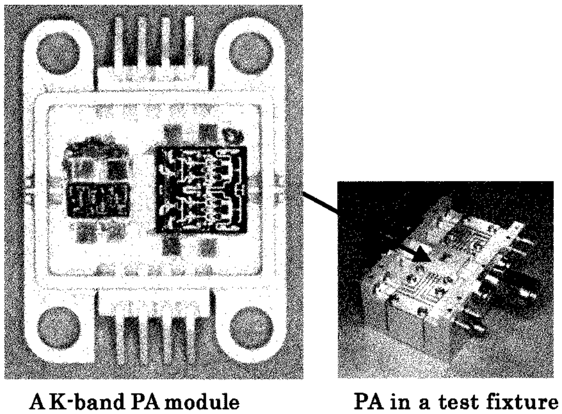


Fig. 1. 23–26-GHz 2-W PA module with driver and PA MMICs.

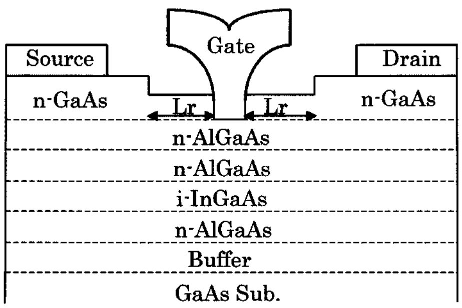


Fig. 2. Structure of a pHEMT applied to the LMDS PA development. The recess length L_{r} was optimized for higher performance.

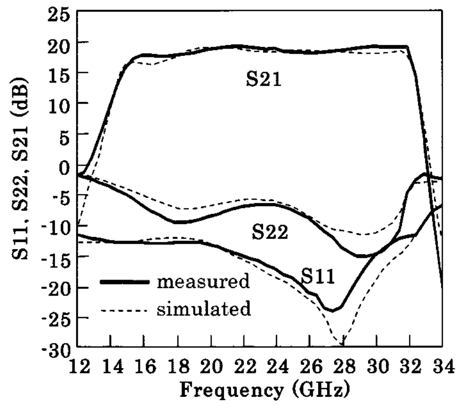


Fig. 3. DA's performance and design accuracy.

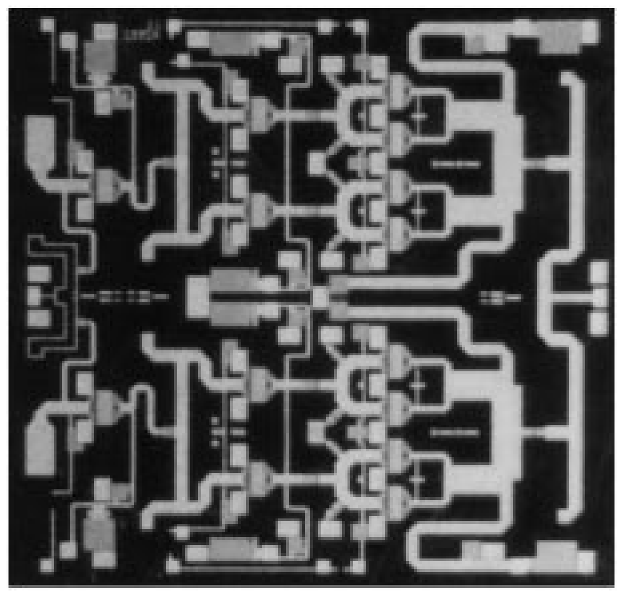


Fig. 4. Microphotograph of a 22–26-GHz 2-W PA MMIC 3.8 × 3.65 mm in size.

layer. These layers were grown by metal–organic vapor phase epitaxy (MOCVD) on a 4-in GaAs semiinsulating substrate. The thickness of the GaAs substrate was thinned down to 28 μm to reduce the thermal resistance. The gate metal is WSi/Au for high reliability. The gate length (L_{g}) is 0.25 μm to obtain a high gain at quasi-millimeter-wave frequencies. This gate is recessed with the cap layer in order to reduce the influence of surface depletion. This recess length (L_{r}) is a dominant parameter that determines the on-resistance (R_{on}) and gate–drain breakdown voltage $(\mathrm{BV}_{\mathrm{gd}})$. We found an optimum L_{r} value that gives the best efficiency at the required output power and the K-band frequency [3].

DAs [4] need to operate in a wide frequency range, hopefully covering all of the LMDS band, for simplifying development of PAs for various frequency bands. The DA is a four-stage completely 50-Ω matched MMIC 2.6 mm $\times$ 1.4 mm in size. Each stage utilizes the power pHEMT in Fig. 2. The gatewidth in each stage is 600, 900, 1050, and 1200 μm, respectively, gradually increasing the width for linear operation, which is most important in the LMDS systems. A distributed amplifier is utilized for the input stage to realize a good input return loss over the frequency range. We employed an accurate distributed small-signal FET model, an active load–pull measurement data on the gate and drain ports, and an extensive electromagnetic (EM) simulation throughout the design, resulting in a very close agreement between the predicted and measured frequency responses, as shown in Fig. 3. The MMIC fabrication process involves ion implantation for isolation, alloyed ohmic contact, air-bridge, metal–insulator–metal (MIM) capacitor, via hole, and plated heat-sink technology. This DA MMIC provides performances valuable for various K-band wireless applications. The performance of this DA at the 1-dB compression point are as follows:

1) $P_{-1\ \mathrm{dB}}$ is larger than 24 dBm;
2) $G_{-1\ \mathrm{dB}}$ is nearly 18 dB;
3) power-added efficiency (PAE) at $P_{-1\ \mathrm{dB}}$ is greater than 15% at frequencies between 17–30 GHz.

A microphotograph of the 22–26-GHz PA MMIC in the module is shown in Fig. 4. Eight 0.25-μm-gate-length pHEMTs, each of which has a 1200-μm gatewidth and the same structure as mentioned above, are incorporated for the final stage to achieve a PA MMIC with a $P_{-1\ \mathrm{dB}}$ of 2 W. This PA is a three-stage completely 50-Ω matched MMIC 3.8 mm $\times$ 3.65 mm in size. The gatewidths for the first and the second stages are 1600 μm $\times$ 2 and 1400 μm $\times$ 4. The gatewidths of the stages were optimized for the best power performance as well as for higher linearity. The design procedure is the same as that of the DA. A couple of 1-W PAs were combined on a chip, the output power combiner of which is less

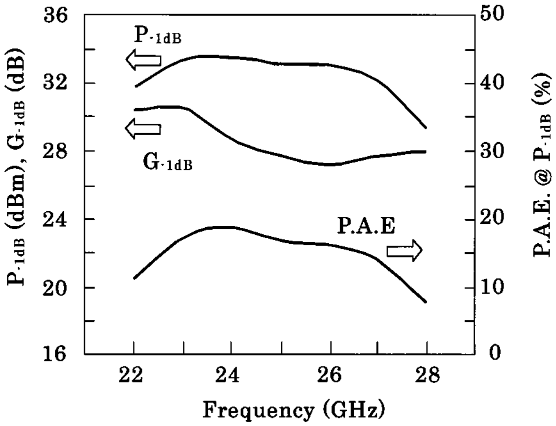


Fig. 5. Frequency responses of a 23–26-GHz 2-W PA module.

than 0.9 dB in insertion loss. The chip was also thinned down to 28 μm to make the chip size smaller and the thermal resistance between channel and case as low as possible. The performance of this PA at the 1-dB compression point are as follows:

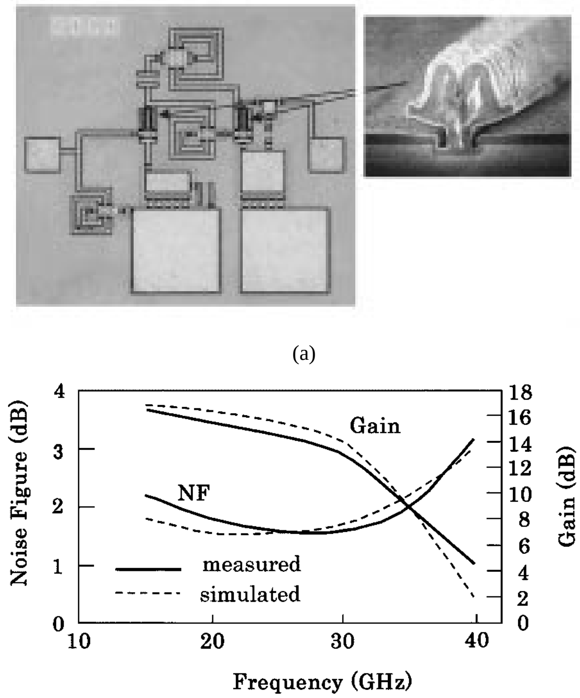
1) $P_{-1\ \mathrm{dB}}$ is 34 dBm;
2) $G_{-1\ \mathrm{dB}}$ is nearly 13 dB;
3) PAE at $P_{-1\ \mathrm{dB}}$ is greater than 25% at frequencies between 22–26 GHz.

age shown in Fig. 1 was designed so as to kill the cavity resonance by optimizing the cavity size and distance between the lid and MMIC surface. The PA module's performance in Fig. 5, which is a combination of $P_{-1\ \mathrm{dB}}$ of 33–34 dBm, $G_{-1\ \mathrm{dB}}$ of 29±2 dB, and PAE at $P_{-1\ \mathrm{dB}}$ of 18%±2% at frequencies between 23–26 GHz, is the highest among ever reported PAs for the K-band wireless application. The temperature dependence of $P_{-1\ \mathrm{dB}}$ is as small as -0.01 dB/°C. This device operates at 7 V and nearly 1.5 A. A figure-of-merit that is a product of gain (in decibels) and a relative bandwidth (in percent) is 3.7, which is nearly two times that of ever reported 2-W PAs.

B. LNA

The LMDS K-band LNA is a device that also needs to be broad band and linear as does a DA and PA. A low noise figure across the LMDS bands and a high gain density are also required for strict cost reduction. Though the design and fabrication technologies of a K-band LNA have matured, the gain density and bandwidth are still to be improved.

Fig. 6(a) shows the microphotograph of a K-band LNA [5], which operates from 19 to 33 GHz. A 0.15-μm-gate pHEMT with an f_{T} of 75 GHz and $f_{\max}$ of 150 GHz was used for low-noise and high-gain operation. This pHEMT utilizes n-InGaP/i-InGaAs layers for the channel. This LNA was newly developed incorporating a complete lumped-element design. Two 80-μm gatewidth pHEMTs were combined in a series bias topology, and the impedance-matching circuits were composed of spiral inductors, resistors, and MIM capacitors. The source current of the second-stage pHEMT is fed to the drain of the first-stage pHEMT through an inductor–resistor circuit as an impedance-matching element. The output of this LNA is resistively impedance matched to save the area for the output matching as well as to achieve broad-band operation. The chip



(a)

(b)

Fig. 6. 19–33-GHz miniature LNA MMIC 1.0×0.9 mm in size. (a) Microphotograph. (b) Broad-band responses.

size is a mere 1.0×0.9 mm. The frequency responses of the gain and noise figure are also shown in Fig. 6(b). A wide-band operation between 19–33 GHz is achieved with a noise figure of 1.7±0.2dB and a gain of 14.5±2 dB, with reasonably good return loss at 2.5 V and 7.5 mA. A good linearity, an OIP_3 of 20 dBm, was obtained from this LNA topology due to very low substrate current.

The packThe gain density in dB/mm^2 and a figure-of-merit defined as $\Delta f/f_0 \times 1/(F-1)$ are 2.5 times higher than the previous highest record, where $\Delta f/f_0$ is the relative bandwidth and F is real value of the noise figure. This LNA chip size shrinks as the via size shrinks, and the intrinsic circuit area can be as small as 0.6×0.8 mm. The spiral inductor was proved in house to be applicable in the whole LMDS band. This makes a low-noise gain block significantly cost effective.

C. Multiplier (×4)

The wide-spectrum allocation for the LMDS and other wireless applications makes it difficult to produce oscillators and VCOs that are available across the frequency range. Commercially available tunable waveguide oscillators using GUNN diodes are expensive (the price is ten times higher than expected). Development and production of the K-band monolithic VCO have not been practical because of the wide-frequency allocation and the required low phase-noise level. Hence, the usual solution is to use multipliers in combination with lower frequency VCOs and phase-locked loops (PLLs). VCOs for other wireless applications are in a similar fashion.

Fig. 7 shows a 9.5/38-GHz pHEMT multiplier MMIC, 2.0×1.7 mm in size, which is comprised of an active-balanced

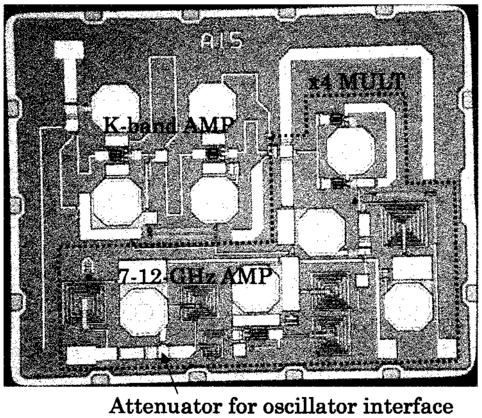


Fig. 7. Microphotograph of a 9.5/38-GHz quadrupler MMIC 2.0 × 1.7 mm in size. An input attenuator of 7 dB is, in this case, implemented for interface to the oscillator.

multiplier by four (quadrupler) and buffer amplifiers. Since the active-balanced quadrupler is a simple combination of common-gate-FET (CGF) and common-source-FET, it is principally broad band. A shunt-open stub at the common drain electrode traps the $2f_0$ component and determines the operating frequency band. Simulated 3-dB bandwidth of the active balanced scheme with a $2f_0$ trap corresponds to one-half of the whole LMDS band. Combining a broad-band input buffer amplifier and the active balanced scheme, a broad-band quadrupler core is realized. The trap and a 38-GHz band amplifier are tuned for the target frequency range. The input buffer amplifier is completely 50-Ω matched in broad band, providing a good interface between a 9.5-GHz-band VCO and the quadrupler. The output 38-GHz-band amplifier selectively amplifies the $4f_0$ component. Both the amplifiers and quadrupler also provide complete suppression of the pulling effect by the load.

The measured frequency responses of a fabricated quadrupler MMIC are shown in Fig. 8. The fourth harmonic $(4f_0)$ of the injected signal (f_0 between 9.2–9.7 GHz) levels at nearly 1 dBm when an 11-dBm fundamental-frequency signal is injected. This quadrupler MMIC includes a 7-dB input attenuator in this case in order to make a good interface to a 9.5-GHz band VCO. The other harmonics are suppressed −20 dBc below the fourth one. The third harmonic level is below −35 dBc. Further suppression of the fifth harmonic is necessary for more practical application. The conversion gain after removing the 7-dB attenuator is nearly −3 dB, where the input port impedance will be nearly 50 Ω due to the CGF's source impedance.

Quadruplers increase the phase-noise level at a rate of 6 dB/octave, while direct oscillators in MMIC form and in conjunction with the dielectric resonator increase the level empirically at a rate of 14 and 19 dB/octave, respectively. This is a reason why multipliers have been used for local oscillators in the K-band communication systems. A 38-GHz-band VCO employing the quadrupler MMIC is introduced in Fig. 9. This VCO module with a cap is $13.7 \times 10.0 \times 3.2$ mm in size. A 9.5-GHz fundamental oscillator is composed of a GaAs MESFET negative-resistance chip and a weakly coupled microstrip resonator on an alumina–ceramic substrate. Due

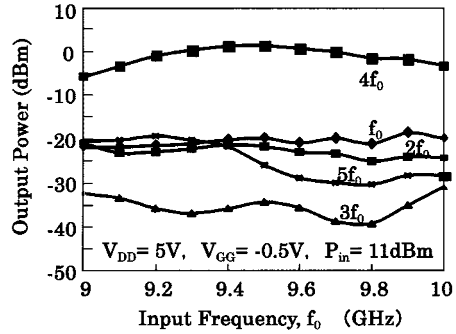
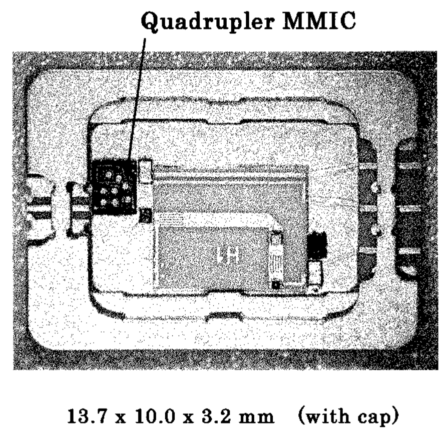
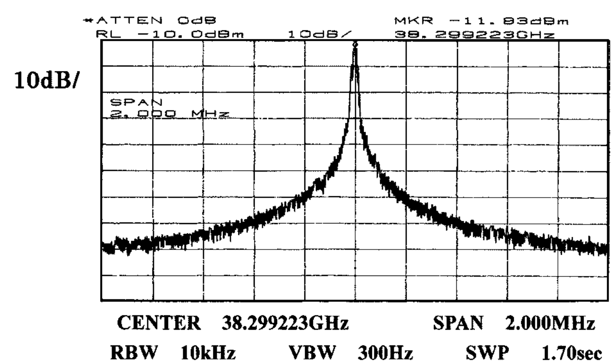


Fig. 8. Measured performance of a 9.5/38-GHz quadrupler.



(a)



(b)

Fig. 9. VCO module incorporating a 9.5/38-GHz quadrupler and a 9.5-GHz VCO. (a) Inside view. (b) 38-GHz-band oscillation spectrum.

to the multiplying effect, the phase-noise level at 100-kHz offset is as low as −90 dBc at 38 GHz. The output power level is nearly 2 dBm and the modulation linearity is less than 2% across a 500-MHz tuning range. A 20-dB improvement in the phase-noise level is potentially achieved by using an Si bipolar junction transistor (BJT) or GaAs heterojunction bipolar transistor (HBT) for the fundamental oscillator.

III. Millimeter-Wave MMIC Technologies

This section focuses on advanced MMIC technologies that are expected to push ahead the progress of millimeter-wave MMICs and modules. The millimeter-wave MMIC production

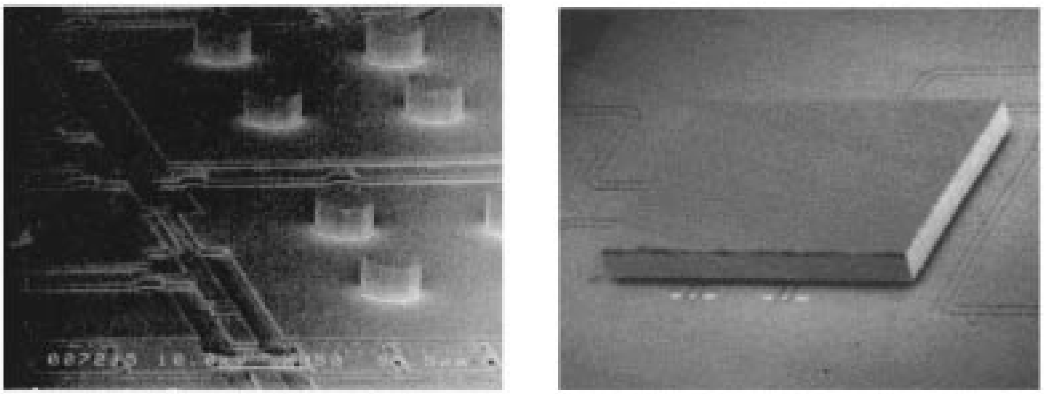


Fig. 10. Gold pillars on a coplanar MMIC surface and a MMIC die flip-chip mounted on an alumina–ceramic substrate.

is now performed using an InGaP/InGaAs/GaAs pHEMT because the InP HEMT has not yet proved itself mass producible. The greatest interests are on MMIC fabrication and assembly technologies. Flip-chip bonding for multichip assembly and a three-dimensional structure for single-chip integration will be discussed.

A. Flip-Chip MMIC

Flip-chip bonding is very effective to remove interconnect mismatches at millimeter-wave frequencies. To perform a flip-chip assembly, the MMIC needs to be coplanar. As frequency increases, the dimension of the coplanar waveguide should decrease for suppression of undesired transmission modes. Hence, tiny and high-density bonding structures have been pursued. The latest flip-chip MMICs for 76-GHz-band automotive radar application utilizes "gold pillars." The gold pillars are simultaneously produced on a MMIC wafer surface in the final stage of the semiconductor process. A scanning electron microscopy (SEM) photograph of the gold pillar structure is shown in Fig. 10. The pillar height and diameter are as small as 22 and 40 μm, respectively. The circuitry is designed using the pHEMT in Fig. 6(a) and the coplanar waveguide. A number of pillars support the MMIC 20 μm above an alumina–ceramic substrate after a pulse–heat mount process. The ground metal on this alumina–ceramic substrate is used as the ground of microstrip lines that have strip conductors on the other side of the substrate [6]. The thickness of the substrate was determined to make the resonant frequency of the feed-through higher than 90 GHz. The insertion loss of each through hole at 76 GHz is 0.5 dB.

The ground metal on the alumina–ceramic substrate exists beneath the MMIC's flip-chip surface, i.e., 20 μm in distance. Counting this structure and its small effect to the EM field, functions such as a 38/76-GHz doubler, 76-GHz amplifier, and 76-GHz mixer, were developed. Packaging of the flip-chip MMIC is simply done by only putting a metal cap over the MMIC, as shown in Fig. 11. The flip-chip mount provides very low loss and reproducible interconnection at millimeter-wave frequencies. We incorporated the gold pillars and the packaging methodology to enhance the flip-chip technology. An issue is to further reduce the total cost for the radar and other consumer applications.

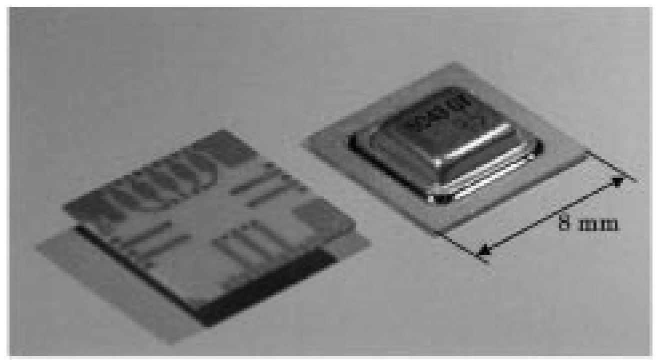


Fig. 11. Effective packaging of flip-chip MMIC.

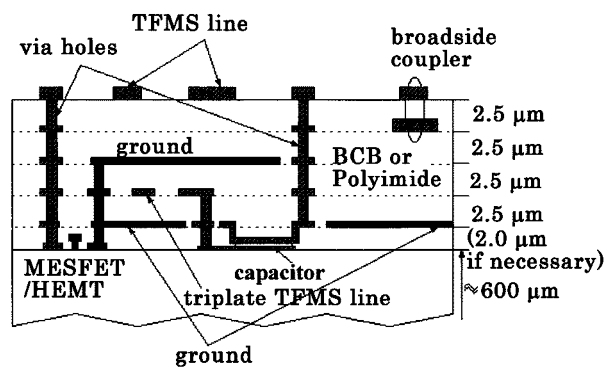


Fig. 12. Cross-sectional view of the 3-D MMIC proposed in [7] (courtesy of the NTT Corporation).

B. 3-D MMIC

The 3-D MMIC that incorporates thin polyimide or BCB layers stacked over a GaAs substrate surface is effective for integrating various functions on a chip. A schematic cross-sectional view of the 3-D MMIC is shown in Fig. 12. The lower level ground plane is put across a very large portion of the chip surface for effective integration of miniature transmission lines. In 1999, the NTT Corporation, Yokosuka, Japan, developed and reported a 3-D MMIC 60-GHz-band down converter [7] and exhibited a high integration implementation of the counterparts. A two-stage LNA, a pair of mixers combined with a 90° coupler, an in-phase divider, and output IF amplifiers are integrated there

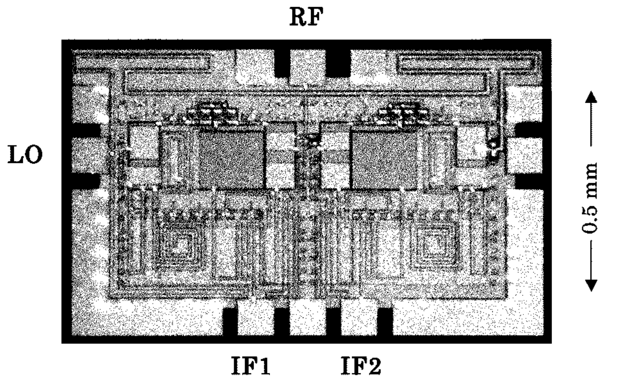


Fig. 13. Microphotograph of an LMDS image-rejection harmonic mixer (lower band) 0.8 × 1.2 mm in size.

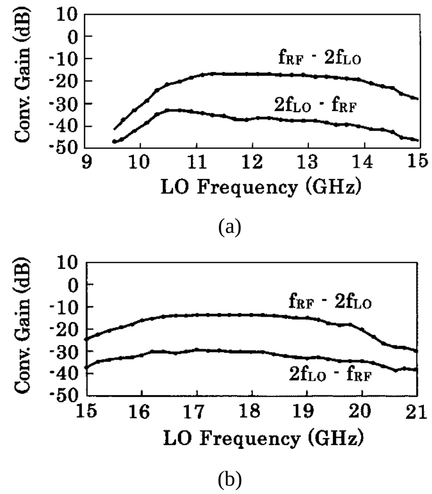


Fig. 14. Measured frequency responses of 3-D MMIC image-rejection harmonic mixers. (a) For the LMDS lower band. (b) For the LMDS upper band.

on a chip a mere 1.84 × 0.87 mm in size. The used transmission lines are miniature thin-film microstrip (TFMS) lines on layers. The integration level is nearly five times that of the planar MMICs. The converter chip has only two millimeter-wave ports: i.e., RF and local oscillator (LO). A gain of 19.3 dB±1 dB, image-rejection ratio of greater than 18 dB, and a noise figure of nearly 7 dB were measured. Even when the number of functions increases, the chip size is still small enough, potentially saving the assembly cost. This 3-D MMIC eliminates the bulk process for each development because a "masterslice" wafer is used [8]. The structure with ground metals and transmission lines on the same side of the chip also meets the flip-chip bonding.

Fig. 13 shows the microphotograph of a K-band image-rejection harmonic mixer that we designed as trial using antiparallel FET–diode pairs and employing the GaAs–MESFET-based 3-D MMIC foundry service by NTT Electronics, Atsugi, Japan. The lower and upper halves of the LMDS band were considered in the design. The mixer in Fig. 13 is for the lower LMDS band, where all the TFMS lines, except the broadside coupler, are implemented on a metal-layer 5 μm above the ground plane on a GaAs substrate surface. The chip size of lower and upper band mixers is 0.8 × 1.2 mm, which is less than 1/5 of that of conventional ones [9]. The intrinsic circuit size is 0.6 × 1.0 mm, including a couple of 0.5 × 0.5 mm harmonic mixers. By combining this mixer with amplifiers, each of which is usually 0.5 × 0.5 mm, harmonic frequency converters can be integrated on a small die. Frequency responses of the mixers are shown in Fig. 14, where the conversion loss is 16 and 13 dB and the image-rejection ratio is nearly 20 dB at a local power level of 11 dBm and an IF frequency of 1 GHz. This harmonic mixer has only one quasi-millimeter-wave port: i.e., the RF port. Frequency of the signal applied to the LO port is between 10–20 GHz. Hence, a simpler assembly can be performed for this quasi-millimeter-wave component.

IV. Comparison to Other Technologies

Other technologies for the same markets and research areas as those described above will now be discussed.

A. PA

The K-band PAs for the LMDS and point-to-point markets are provided based on quarter-micrometer-gate pHEMT process by mainly TriQuint, Richardson, TX, and Fujitsu Quantum Devices (FQD) Limited, Yamanashi, Japan. TriQuint's PAs now exhibit higher performances in "chip" form than FQDs when compared at the current $P_{-1\ \mathrm{dB}}$ level of 1 W. The advantages of the TriQuint PA MMICs are higher gain, higher third-order intercept point (IP3), and smaller die area due to a flatter g_{m} characteristic of the pHEMT and circuit design techniques. The design techniques are extensive use of EM simulation, the process availability of MIM capacitors over dry-etched vias, and the acceptance of a greater design risk [10]. They employ 100-μm -thick wafers to perform chip business. The advantages of the FQD PAs are use of very thin (28 μm) wafers that potentially shrinks the die area beyond TriQuint's when dry vias are introduced. The other advantage of FQD PAs is that they are assembled in a package with a DA to meet the market requirements. The 28-μm-thick wafer technology and the low-cost K-band package are the results of a lot of know-how. The 2-W packaged PA described in Section II-A is a very new product leading the LMDS and point-to-point radio markets. A 0.15-μm-gate pHEMT was also applied to the PA development. Some newly developed PA MMICs exhibited an IP3 of 2 dB higher than TriQuint's.

B. LNA and VCO

United Monolithic Semiconductors (UMS) is also a well-known provider of MMICs. The main products of UMS are LNAs, mixers, and DAs. K-band LNAs have been delivered mainly by UMS with a noise figure of 2 dB. They use a quarter-μm-gate pHEMT for the LNAs. FQD recently released K-band LNAs, including the LNA shown in Section II-B, based on a 0.15-μm-gate pHEMT process, easily achieving a noise figure of 1.8 dB for the same gain level. Other companies have not yet delivered LNAs for the market.

The VCO is a key device for the LMDS equipment, as well as PAs and LNAs; however, very few MMIC-based products can be found. Hittite Microwaves, Woburn, MA, announced a VCO as is for the LMDS use. The most important performance is a lower phase noise level to be achieved at a low cost. The required higher performance makes it difficult to release MMIC-based

VCO products. Many of current LMDS units employ a low-cost microwave VCO and a multiplier chain with discrete devices. The quadrupler MMIC concept in Section II-C can be a solution.

C. Advanced MMIC Technology

Flip-chip bonding has been considered to be essential for reproducible millimeter-wave interconnections, and there are many conference reports on it. However, millimeter-wave products based on the technology are not yet popular in market because the millimeter-wave market is still small. NEC, Otsu, Japan, has recently reported a 60-GHz wireless adapter module and a 76-GHz automotive radar module by using 60-μm-high gold stud bumps, which are to be thermo-compressed to 20 μm to implement MMICs in a low-temperature co-fired ceramic (LTCC) multilayer package [11], [12]. The bumps are formed on an alumina substrate. Accuracy of the FQD's flip-chip bonding in Section III-A is considered to be higher than the other ones because the gold pillars are directly fabricated on a MMIC. The 3-D MMIC using polyimide layers in Section III-B was firstly reported by NTT in 1996. The research of IBM, Lowell, MA, and Texas Instruments Incorporated, Dallas, TX, were also reporting applications of polyimide film(s) on MMICs for implementation of low-loss transmission lines on Si substrate or for simple shielding of amplifiers[13], but not for high integration of functional circuits. In other way, the 3-D structure is widely used for a high-Q inductor on a MMIC.

V. Conclusion

The recent progress of K-band and millimeter-wave MMIC technologies has been shown by demonstrating recent PAs, LNAs, multipliers, and flip-chip MMICs, and a novel 3-D MMIC. The K-band MMICs that are now in the LMDS and point-to-point radio markets are still being improved due to customer requirements. The 3-D MMIC and flip-chip MMIC have excellent features for chip-size reduction and assembly cost saving, though these technologies have not yet matured. Both technologies can play an important role in future millimeter-wave applications.

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