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SILICON BIPOLAR MMIC FOR FREQUENCY-CONVERSION APPLICATIONS UP TO 20 GHz

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ABSTRACT

A simple yet versatile silicon bipolar monolithic microwave integrated circuit (MMIC) is presented that can be utilized in a variety of frequency conversion applications. With an external feedback network the MMIC functions as a regenerative frequency divider for input signals up to 20GHz. It can also be used as an unbalanced active mixer with conversion gains up to 10dB at 10GHz. With an external resonator it functions as a self-oscillating mixer (SOM) with conversion gains up to 17dB at 5GHz.

INTRODUCTION

Low cost, small size, reproducible performance and multi-functional integration are the desired attributes of the next generation of microwave components. MMICs are developing as a class of circuits that can potentially fulfill these requirements by displacing specific hybrid circuits and subsystems. This paper presents a simple silicon bipolar MMIC that challenges GaAs MMICs in a variety of frequency conversion applications for input signals up to 20GHz.

Three frequency conversion applications using the MMIC will be discussed. First, a family of divide by 2 regenerative frequency dividers with operating bandwidths up to 20%, exhibiting conversion gain (instead of the typical conversion loss) and functioning for input signals from 4 to 20GHz will be presented. Frequency dividers are important building blocks used in synthesizers, frequency counters and spectrum shaping circuits. Second, the performance of the MMIC as an unbalanced active mixer, again exhibiting conversion gain for input signals up to 12GHz, will be reviewed. Finally, the performance of the MMIC as a SOM using a dielectric resonator will be reported.

CIRCUIT CONFIGURATION AND FABRICATION PROCESS

The basic circuit topology of the MMIC (Fig. 1) consists of a self-biased, silicon bipolar Darlington pair, and is identical to the one which has been shown to be effective for broadband amplification up to 6GHz [1]. For nonlinear applications, to avoid negative feedback, the value of the resistors is very high. For oscillator and mixer applications, transistor Q1 is the nonlinear element that both limits the amplitude of oscillation and generates the frequency products. Transistor Q2 operates as an output amplifier. There are a number of advantages of using a Darlington pair over a single transistor. First, the Darlington pair has current gain at higher frequencies, thus significantly extending the upper limit of the frequency of operation. Second, a properly sized and biased Darlington pair will have a lower reflection coefficient at microwave frequencies than a single device, facilitating the matching of the device and enabling operation over a broader frequency band. Furthermore, for SOM applications, the biases of Q1 and Q2 are set to independently control the amplitude of oscillation and the conversion gain, adding one degree of freedom to the design.

The MMIC was fabricated using an f_T=10GHz nitride self-aligning process featuring interdigitated 0.75 micrometer-wide arsenic-doped emitters with 4 micrometers emitter-to-emitter pitch, 2 micrometers-thick local oxide isolation, ion implantation, thin-film polysilicon resistors and gold metallization. Since the maximum frequency of oscillation (fmax) of a bipolar transistor is inversely proportional to the emitter width and to the emitter to emitter pitch, submicrometer photolithograpy was a key element in obtaining a basic transistor with a higher than 20GHz fmax (where the maximum available gain equals 0dB). The extremely small die size (0.3mm x 0.35mm) and the single bias supply requirement of the MMIC allow compatibility with low-cost, standard microwave transistor packages.

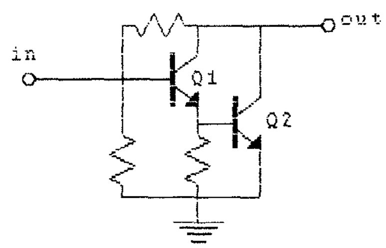

Figure 1. MMIC equivalent circuit

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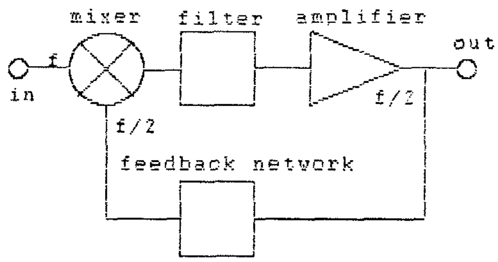

Figure 2. General concept of regenerative frequency divider

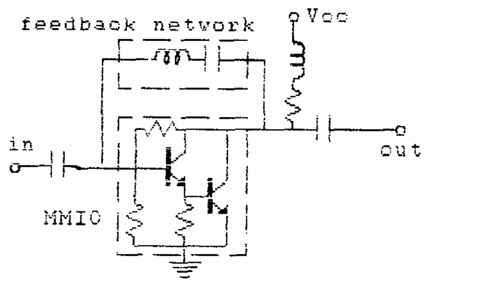

Figure 3. Frequency divider using MMIC

REGENERATIVE FREQUENCY DIVIDER

The general concept of the regenerative frequency divider (Fig. 2) has been known for quite some time [2]. The required functions include mixing, amplification and filtering. To understand the circuit's operation, it is assumed that a signal at a frequency f/2 exists somewhere in the loop. When an input signal at frequency f is applied, it mixes with the f/2 signal, generating products at f/2, f, 3f/2, etc. The signal at f/2 is filtered out, amplified and fed back to the mixer. If with the input signal applied, the open-loop gain is greater than 1 at the subharmonic, this signal will be sustained in the loop.

Early implementations of the divider used discrete components to realize the mixer, amplifier and filter functions [3,4]. A monolithic implementation that integrates all the functions in a single silicon bipolar MMIC has been reported [5]. In a variation of the same oncept, the mixing and subharmonic amplification functions were merged in a single GaAs FET using MIC [6] and MMIC [7] technologies, and for RF frequencies in a single bipolar transistor [8]. This work presents a similar approach, where a Darlington pair provides mixing, filtering and subharmonic amplification.

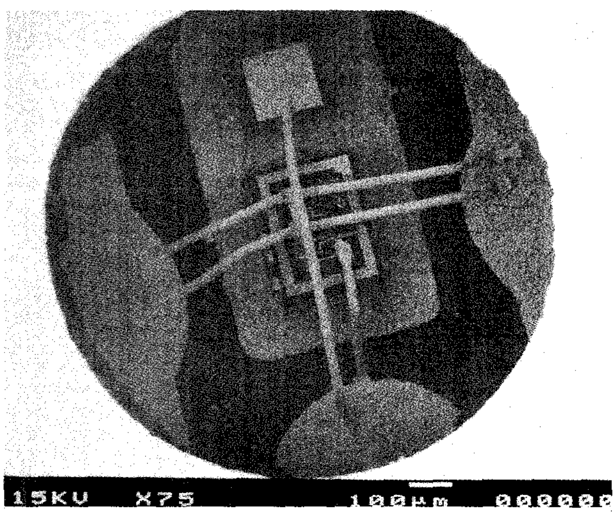

Figure 4. Microphotograph of the complete frequency divider including the MMIC and feedback network in a 70 mil microstrip ceramic package.

Figure 3 shows the frequency divider concept using the Darlington pair. It consists only of the MMIC and of a parallel feedback network. Due to the small die size and the single supply requirement of the MMIC, the complete frequency divider, including the feedback network, can be assembled in a standard microwave transistor package (Fig. 4). The division operating band is set by properly selecting the elements in the feedback resonator. Figure 5 shows the spectrum analyzer plots of the output port as an input signal is swept over the indicated frequency ranges for 4 typical frequency dividers that were fabricated. The percent operating bandwidths are (a) 21%, (b) 20%, (c) 18% and (d) 2%. The MMIC is biased at 45mA and 8V (from a 15V supply and a 155ohm resistor). Figure 6 shows the turn-on threshold input power as a function of input frequency and the conversion gain versus input power for the 11.6-14.2GHz divider.

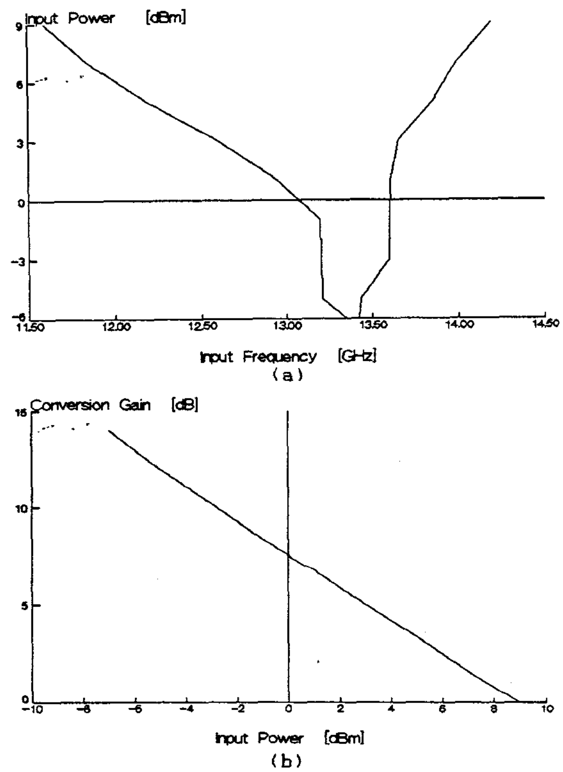

Figure 6. 11.6-14.2GHz divider. (a) Turn-on threshold input power vs. input frequency. (b) Conversion gain vs. input power, fin=13.4Ghz.

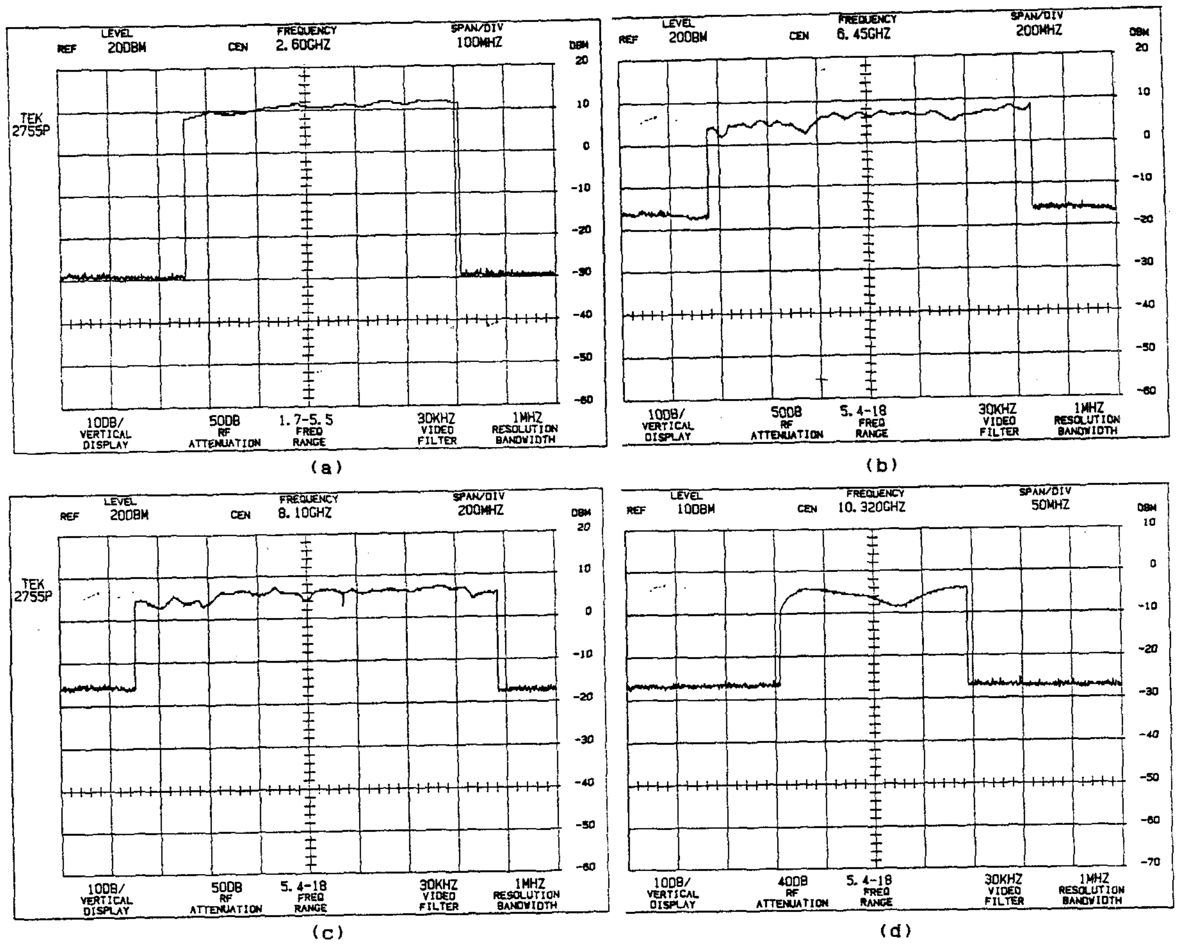

Figure 5. Output spectrum of four typical frequency dividers.
Input signal bands: (a) 4.7-5.8GHz, +7dBm; (b) 11.6-14.2GHz, +9dBm; (c) 14.8-17.7GHz, +12dBm; (d) 20.45-20.85GHz, +14dBm.

ACTIVE MIXER

The MMIC can also be used as an unbalanced active mixer when both the LO and RF signals are applied at the input. Figure 7 shows the performance of the mixer for television receive-only (TVRO) and direct broadcast satellite (DBS) applications. With the MMIC biased at 35mA, Figure 7(a) shows the conversion gain versus RF frequency when a +5dBm LO signal is injected at 5.15GHz. Figure 7(b) shows the same plot, with a +7dBm LO signal at 10.75GHz. Depending on the IF frequency, more than 10dB of conversion gain can be achieved. Figure 8 shows the performance of the mixer with a high-side swept LO, for two different IF frequencies. For the 70MHz IF, a 0dBm LO is injected. For IF=1GHz, a +5dBm LO is injected. When using the MMIC as an unbalanced active mixer, external filters are required if isolation between ports is desired.

SELF-OSCILLATING MIXER

The MMIC can be used as a two-port oscillator if a feedback resonator is added and the Barkhausen criteria for oscillation are satisfied. When the circuit oscillates, if a signal is present at the input, it mixes with the LO signal generating the frequency products. A complete analysis of the circuit as a SOM using a

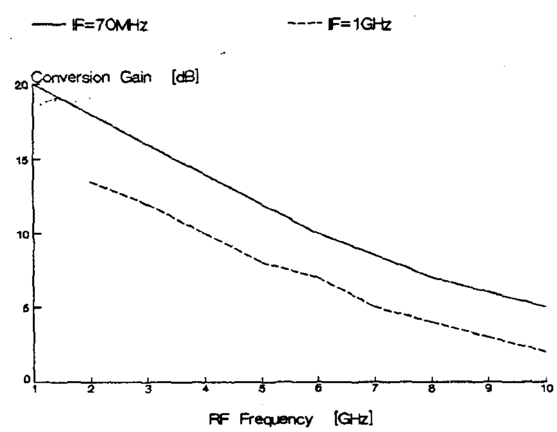

Figure 8. Conversion gain vs. RF frequency for two different IF frequencies. Active mixer application.

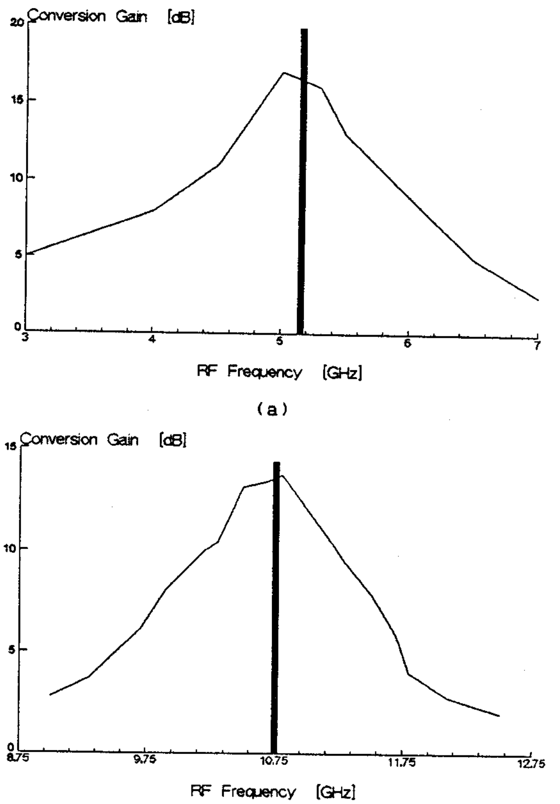

Figure 7. Conversion gain vs. RF frequency for (a) TVRO, and (b) DBS bands. Active mixer application.

dielectric resonator has already been reported [9,10]. The results are summarized here for completeness, as another frequency-conversion application of the MMIC. Using a 5GHz dielectric resonator a TVRO down-converter was realized. The SOM board including the MMIC, dielectric

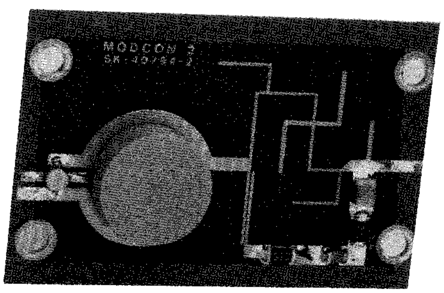

Figure 9. TVRO SOM board showing MMIC, dielectric resonator, output filter and bias.

resonator, output filter and bias is shown in Figure 9. The input band from 3.7-4.2GHz was converted to the 0.95-1.45GHz IF band. With the MMIC biased at 35mA it exhibits 9 ± 1 dB conversion gain, 12dB SSB noise figure, input and output VSWRs better than 2.5:1, +8dBm output compression point, +17.5dBm two-tone third-order intercept point, and inband single-tone intermodulation suppression greater than 70dBc (for -20dBm input power). The highest measured frequency of oscillation for a microstrip packaged MMIC was 10.7GHz, using the proper dielectric resonator.

SUMMARY AND CONCLUSIONS

A simple yet versatile silicon bipolar MMIC has been presented that can be utilized in a variety of frequency-conversion applications up to 20GHz. Silicon bipolar transistors with 0.5 micrometer emitter width, 2 micrometer emitter-emitter pitch and fmax greater than 35GHz have already been reported [11]. This promises applications for these devices at even higher frequencies.

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