Monolithic 38 GHz Coplanar Feedback VCOs Fabricated by a Production PHEMT Technology

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***Abstract* — A set of coplanar 38 GHz voltage-controlled oscillators has been developed. The oscillators are based on a feedback topology and consist of a two-stage amplifier, a frequency selective feedback network, and a voltage-controlled phase shifter. The monolithic circuits also include a buffer stage and were fabricated by a production-oriented PHEMT technology. By employing different feedback networks and phase shifters according to a building block concept, several versions with tuning bandwidths between 0.6 GHz and 1.3 GHz have been realized. The oscillators show a high tuning linearity and an almost constant output power of typically 12 dBm.**

I. Introduction

Microwave oscillators are usually designed as negative-resistance circuits. This is the only possible circuit topology if the active component is a two-terminal device as, for instance, a Gunn or Impatt diode. If, however, a three-terminal device like a gallium arsenide (GaAs) transistor is available, an oscillator design may also be based on a feedback topology. In this case, the first step is to design a two-port amplifier employing the active device. Then, a passive three-port network is added, which feeds a fraction of the amplifier output signal back to the input port and also transfers another part to the external load. The attenuation and the phase shift of the feedback path have to be chosen in order to meet the oscillation conditions for magnitude and phase of the loop gain.

The feedback topology may result in a more complex circuit than a negative-resistance approach. This might be the reason why only few examples of feedback oscillators in the microwave and millimeter-wave frequency range have been published so far [1]-[6]. The feedback concept offers, however, a number of advantages. There is a more distinct relation between the different circuit elements and the oscillator parameters. The amplifier design defines the range of possible oscillation frequencies and sets the limits for the loop gain and the available output power. These limits can be extended by using more than one stage. With a fixed amplifier circuit, the oscillation frequency is precisely controlled by the transmission phase of the feedback path which usually includes some type of resonator. The corresponding attenuation determines the ratio of the power delivered to the load to that dissipated in the resonator. By modifying this ratio, the designer can find the best balance of output power, phase noise and loop gain. Finally, the feedback topology lends itself to dividing the complete oscillator into a number of functional building blocks. This offers the opportunity to easily adapt the oscillator properties to different system requirements by simply combining different building blocks.

This paper reports on the first realization of monolithic feedback oscillators at 38 GHz with emphasis on the building block concept. The voltage-controlled oscillators (VCOs) have been designed using coplanar waveguide (CPW) transmission lines. The monolithic microwave integrated circuits (MMICs) were fabricated by a GaAs pseudomorphic high electron mobility transistor (PHEMT) technology.

II. Circuit Design

Fig. 1 shows the general block diagram of the oscillators. A two-stage amplifier forms the active part of the oscillating loop. The output signal of this amplifier is split by a Wilkinson type power divider. One part is transferred to the external load via an attenuator and a buffer stage. The other part is routed back to the amplifier input port in order to achieve a continuous oscillation. The feedback path consists of a frequency selective two-port network and a voltage-controlled phase shifter. The latter component is used to control the phase of the loop gain and, in effect, the oscillation frequency.

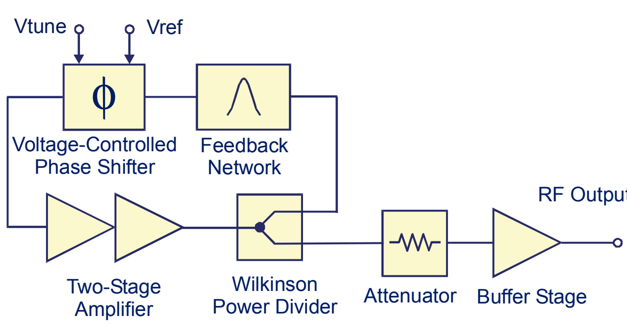

Fig. 1. Block diagram of the monolithic voltage-controlled oscillators with feedback topology.

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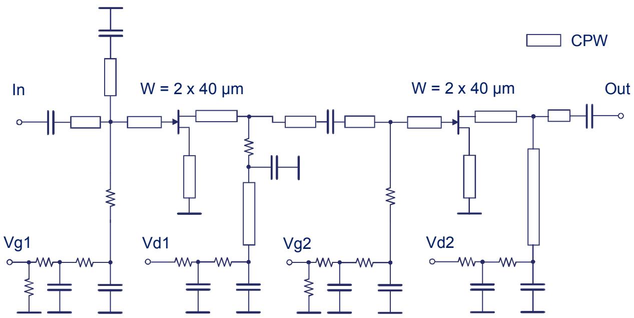

Fig. 2. Schematic diagram of the two-stage amplifier.

The schematic diagram of the two-stage amplifier is depicted in Fig. 2. HEMT devices with 80 µm gate width are used in both stages. The transistors are operated at 20 mA drain current and a drain-to-source voltage of 3 V. The matching networks consist of CPW transmission line sections and lumped MIM (metal-insulator-metal) capacitors. Due to inductive source feedback and resistive low-pass filtering in the DC bias lines the amplifier is unconditionally stable. At 38 GHz, the simulations predict a small-signal gain of 16 dB and an output power of 13 dBm at the 1-dB compression point. The single-stage buffer amplifier has a similar topology.

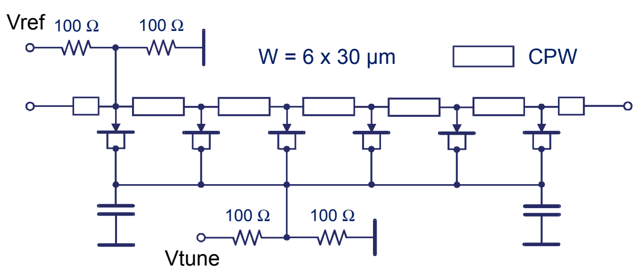

Fig. 3. Schematic diagram of the voltage-controlled phase shifter with 6 varactor HEMTs.

Fig. 3 shows the schematic diagram of one version of the voltage-controlled phase shifter. It consists of 6 HEMT devices with a gate width of 30 µm each and a number of CPW transmission line sections. The HEMTs are operated as passive varactors in shunt configuration with both drain and source nodes connected to RF ground. The combination of the varactor shunt capacitance with the series inductance of the CPW sections results in an artificial transmission line structure. The transmission phase is controlled by the DC voltage applied to the HEMTs. Due to a DC floating ground the tuning voltage range can be shifted linearly by means of the reference voltage V_{ref}. Thus, with an appropriate setting of V_{ref}, the tuning voltage V_{tune} does not need to change its polarity across the whole phase shift range. Both voltages are applied to the HEMT devices via 2:1 resistive dividers. Under small-signal conditions, the transmission phase can be changed by more than 30° at 38 GHz. Depending on the RF voltage amplitude, this value is somewhat lower for large-signal operation.

With a second version of the circuit, a larger phase variation of almost 60° is achieved by extending the number of varactor HEMTs to a total of 10.

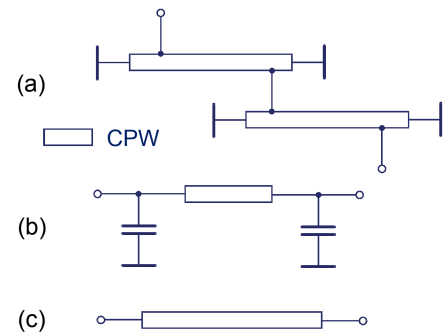

Fig. 4. Feedback networks with different frequency selectivity; coupled half-wavelength resonators (a), filter with transmission line and capacitors (b), plain transmission line (c).

For a given combination of an amplifier and a phase shifter, the tuning range of the oscillator primarily depends on the feedback network shown in the block diagram (Fig. 1). A highly frequency selective network, for instance a narrow-band transmission line resonator, will lead to a small tuning range and vice versa. A smaller tuning range usually is accompanied by better frequency stability and lower phase noise. Fig. 4 shows three different feedback networks which have been adopted in the oscillator designs. The highest selectivity is obtained by a filter with two coupled half-wavelength resonators (a). The second filter network (b) has a broader bandwidth and consists of a CPW section and two MIM capacitors. And, finally, the simplest form of the feedback network is a plain transmission line (c).

TABLE I
38 GHz FEEDBACK OSCILLATOR LAYOUT VERSIONS

VCO	Feedback Network	Number of Phase Shifter Varactors	Chip Dimensions [mm]
#1	a	6	1.70 × 2.96
#2	b	6	1.46 × 2.96
#3	c	10	1.42 × 2.94

The available building blocks have been combined to yield three versions of the 38 GHz feedback oscillator. The two-stage amplifier, the power divider, the attenuator, and the buffer stage are the same for all versions.

However, as shown by Table I, different feedback networks and phase shifters are used. VCO #2 has the same phase shifter as version #1 but a feedback network with less frequency selectivity. For VCO #3 the phase shifter with 10 varactor HEMTs is combined with a plain transmission line as the feedback network. The different building block combinations primarily affect the tuning bandwidth of the oscillators. VCO #1 will have the smallest, version #3 the largest tuning range. The chip dimensions are very similar for all designs and correspond to GaAs areas between 4.2 mm² and 5.0 mm².

III. MMIC Fabrication

The monolithic oscillators have been fabricated on 4-inch GaAs wafers with MBE (molecular beam epitaxy) grown active layers. Optical lithography is applied throughout the whole process including the formation of the gates which have a typical length of 0.13 µm. A high-volume production at low cost is possible since no electron-beam lithography is required and also, due to the coplanar circuit layout, no via holes and no backside metallization. Table II summarizes the main DC and RF parameters of the active HEMT devices. A more detailed description of the fabrication technology is given in [7].

TABLE II
HEMT DC and RF Parameters

Pinch-Off Voltage	-0.5 V
Maximum Drain Current	650 mA/mm
Maximum Transconductance	700 mS/mm
Gate-to-Drain Breakdown Voltage	4 V
Max. Current-Gain Cutoff Frequency	110 GHz
Maximum Frequency of Oscillation	> 200 GHz
Minimum Noise Figure @ 12 GHz	0.6 dB
Output Power Density	150 mW/mm

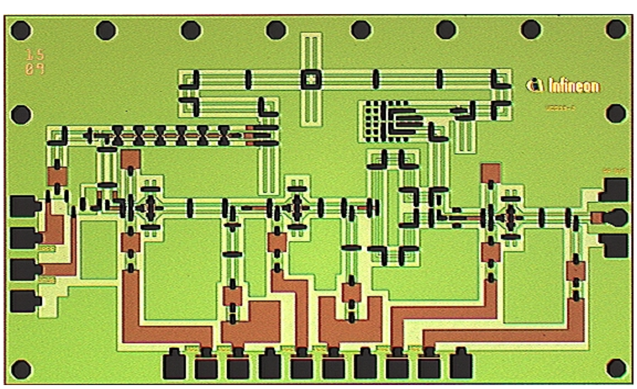

Fig. 5. Chip photograph of version #1 of the monolithic feedback VCO.

Fig. 5 shows a photograph of version #1 of the monolithic VCO. The feedback network with the folded layout of the two coupled resonators is visible in the upper central part of the chip. Located below to the left is the voltage-controlled phase shifter. The lower part of the photograph shows from left to right the two-stage amplifier, the power divider, and the buffer stage. All CPW transmission lines have a finite ground width to avoid the propagation of parasitic modes.

The oscillator chips are suitable for both wire-bond and flip-chip mounting techniques.

IV. Measurement Results

Examples of measurement data for the three versions of the monolithic feedback VCO are shown in Figs. 6-8. A reference voltage setting of $V_{ref} = +2.5$ V results in a single-polarity external tuning voltage range of $V_{tune} = +0.5...+4.5$ V. Since the tuning voltage is applied to the connected drain and source nodes of the varactor HEMTs instead of the gates, the monotonous frequency curves have a positive slope. The tuning sensitivities show only minor variations across the entire frequency range. This feature has already been observed with a previous feedback VCO [4] and appears to be a further advantage of the basic circuit concept. A high tuning linearity is of particular importance if the oscillation frequency is to be stabilized by an automatic control circuit as, for instance, a phase-locked loop.

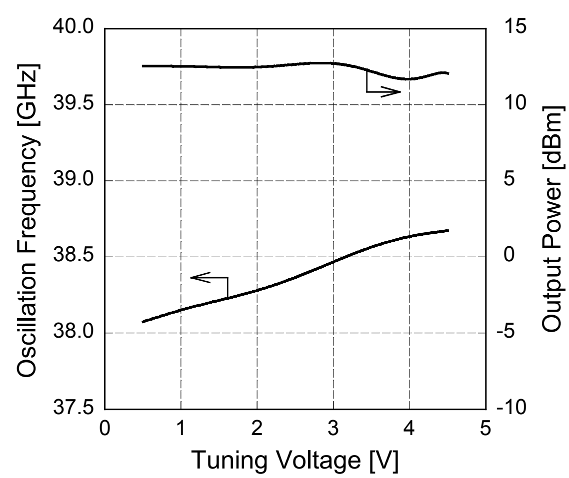

Fig. 6. Measured frequency and output power of VCO #1 as a function of the external tuning voltage.

The measured sample of VCO #1 can be tuned from 38.07 GHz to 38.67 GHz, corresponding to a tuning bandwidth of 0.60 GHz. The electronic tuning range of the

VCO #2 chip extends from 37.89 GHz to 38.74 GHz, resulting in a bandwidth of 0.85 GHz. The VCO #3 sample has a bandwidth of 1.28 GHz ranging from 37.82 GHz to 39.10 GHz. These bandwidths are in agreement with those predicted by large-signal simulations. The same holds for the oscillator output powers. The measured values of 12.3±0.6 dBm, 12.2±0.8 dBm, and 12.0±0.9 dBm, respectively, exhibit both a weak dependence on the oscillation frequency and only small differences between the versions. This demonstrates that the feedback topology allows for an easy change of one oscillator parameter, in this case the tuning bandwidth, without severely affecting other properties.

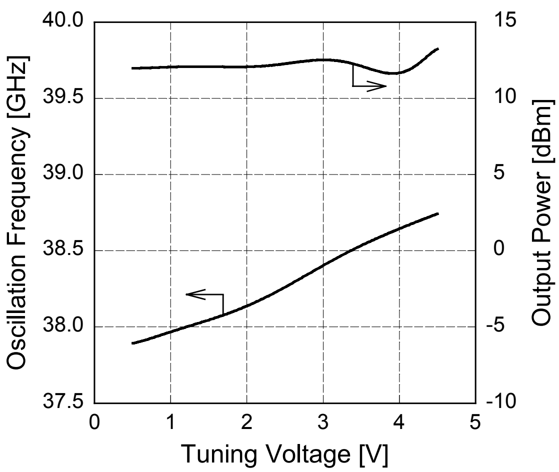

Fig. 7. Measured frequency and output power of VCO #2 as a function of the external tuning voltage.

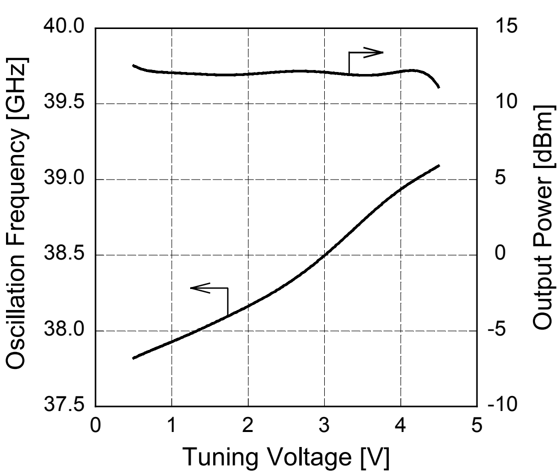

Fig. 8. Measured frequency and output power of VCO #3 as a function of the external tuning voltage.

The phase noise performance of the oscillators has been estimated based on spectrum analyzer measurements. At 1 MHz offset frequency, single-sideband noise-to-carrier ratios of -84 dBc/Hz, -81 dBc/Hz, and -79 dBc/Hz have been obtained for VCO versions #1 to #3, respectively. These measurement results show the expected relation between phase noise and tuning bandwidth.

V. Conclusion

For the first time, the feedback topology has been adopted for the design of monolithic 38 GHz voltage-controlled oscillators. The results confirm the principal advantages of the feedback concept compared to the negative-resistance approach. In particular, the possibility of a building block design methodology has been utilized for an easy realization of oscillators with different tuning bandwidths. The monolithic circuits combine high tuning linearity with reasonable output power. Due to the coplanar circuit layout and the volume-oriented PHEMT fabrication technology, the oscillators are suited for a low-cost production. They may be used in millimeter-wave communication systems and, when followed by a frequency doubler, as the signal source of 76 GHz automotive radar systems.

References

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