The Distributed Oscillator at 4 GHz

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***Abstract*— This paper describes the design and experimental verification of a tunable oscillator based on a microwave distributed amplifier. The oscillator met design expectations, being capable of continuous tuning over the range 1–3.5 GHz with good spectral purity.**

***Index Terms*—Distributed amplifier, tunable oscillator.**

I. Motivation

COMMERCIALLY available wide-band voltage-controlled oscialltors (VCO's) provide us with tunability of about one octave. VCO's possessing higher tunability exhibit worse spectral purity. Another kind of broad-band tunable oscillator using a yttrium–iron–garnet (YIG) resonator possesses very wide-band tuning and good spectral purity. Unfortunately, the tuning of YIG oscillators depends on externally supplied magnetic fields. An instant change of the magnetic field is not easy, nor is the provision of such a field in a monolithic microwave integrated circuit (MMIC) configuration.

We have investigated a new oscillator arrangement which is based on a distributed amplifier. A distributed amplifier is well suited for planar technology and could result in an MMIC with affordable price.

A distributed amplifier is very broad-band in nature. A way of converting a distributed amplifier into a distributed oscillator has been proposed by Aitchison [1]. A distributed oscillator was predicted to be electronically tunable by differentially biasing one pair of active devices at a time. The tuning range depends on the number of stages, with tuning ranges of over one decade attainable. We verified this idea by an experimental sample of the distributed oscillator at 100 MHz [2]. The experimental sample met expectations, working well and verifying the original idea. Measurements of the distributed oscillator have proved some advantages over other oscillators, like good spectral purity and wide-band tuning. Considerable supression of (spurious) harmonics has been achieved as well as continuous tuning over a range of 1–3.

Still, we have found one problem remaining: the tuning function. The tuning function is the dependence of oscillation frequency on gate bias voltages (e.g., on tranconductivity of active devices). Tuning function predicted as a result of linear circuit analysis corresponds to oscillation build-up. When oscillating, the circuit operation is far from linear and one cannot define differential transconductance depending on gate bias voltage. Moreover, drain voltages of the active devices are affected by the oscillations as well.

Commercially available distributed amplifiers are very wide-band in nature. A three-stage oscillator in our arrangement has provided for a tuning band 1–3.5.

Artificial transmission lines possessing critical frequencies of up to 50 GHz are achieved in modern MMIC's. For this reason, we decided to investigate this new kind of oscillator, both theoretically and experimentally, at a "real microwave" frequency.

Manuscript received March 30, 1998; revised September 3, 1998. This work was supported by the Grant agency of the Czech Republic under Grant 102/97/1224.

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Publisher Item Identifier S 0018-9480(98)09214-X.

II. Theoretical Background of the Distributed Oscillator

A. Distributed Amplifier

The microwave distributed amplifier consists of a pair of artificial transmission lines which are coupled trough distributed common source active devices [field-effect transistors (FET's)]. Input signal is fed into the gate line, drives all transistors, and finally vanishes in the gate load. The signals, amplified by each transistor, are of the same phase at the drain line output, which is the output of the device. The signals in the drain line are divided and propagate in forward and reverse modes. The forward mode signals reach the load with the same phase. The reverse mode signal is distorted by antiphase interferences and dissipated by a resistor in an idle drain line load.

B. Reverse Gain Loopback

In [1], the authors introduced the idea of omitting the drain line resistor while connecting the former idle drain output directly to the distributed amplifier input. This approach makes use of the so-called reverse gain to form an oscillation loop. The remaining amplifier port now becomes an oscillator output (see Fig. 1). Each oscillator section consists of two artificial line sections, one of those connected to the drain, the other to the gate of the transistor. Provided only one of the transistors is biased in the active region, the oscillation frequency depends on the position of the active transistor, with respect to the rth active section. The oscillation frequency can be obtained from the equation

$$2 \cdot k \cdot \pi = (2 \cdot r - 1) \cdot \Phi(f_{\rm osc}) + \pi \quad (1)$$

where Φ is the phase shift over one artificial transmission line section, r stands for active section position, and π stands for a phase shift caused by an active FET in a common source arrangement.

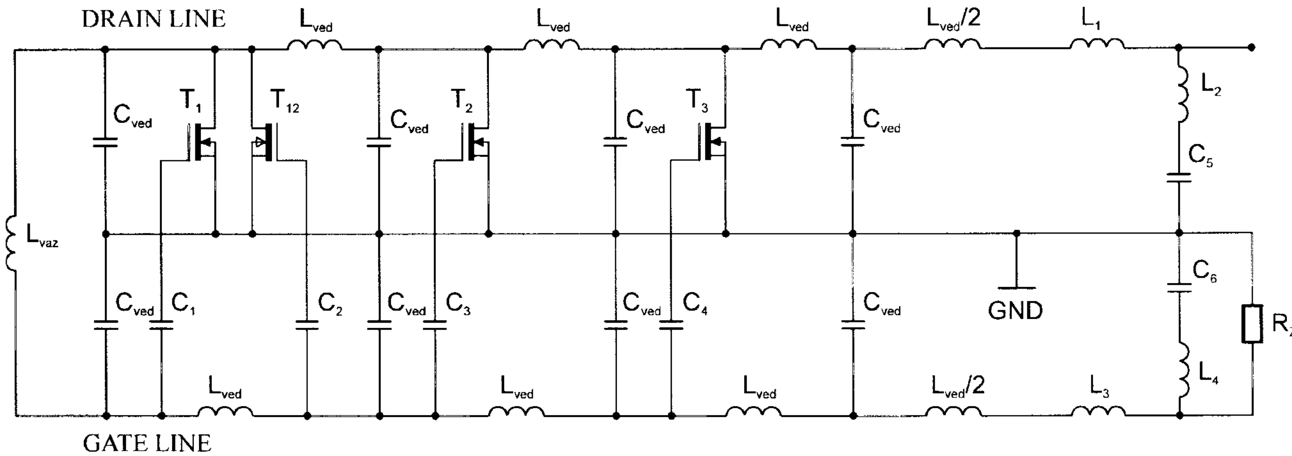

Fig. 1. An idealized schematic chart of a distributed oscillator. Transistor T_{12} overcomes tuning problems at $0.7f_c$.

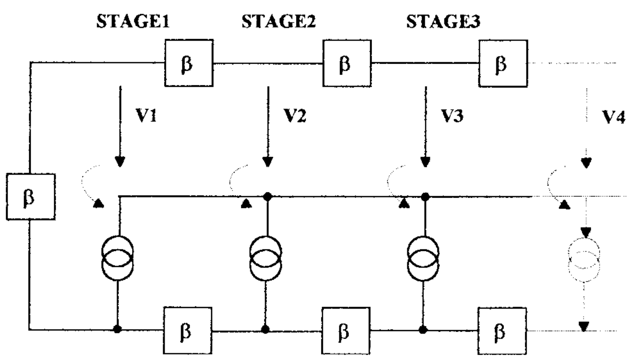

Fig. 2. A simplified schematic diagram of the oscillator. π-networks are pictured as phase-shifting elements possessing a shift of β.

The oscillator is capable of oscillating between two discrete frequencies belonging to single transistors if two FET's are biased in the active region at the same time. The oscillation frequency is given by total phase path of the oscillation loopback. The phase path is calculated as a vector sum of two phase paths per two active FET's with different positions and tranconductance. In this manner, the oscillator can be tuned for all frequencies within its tuning range, with one exception. The exception comes into effect if the phase difference between two active paths approaches π. A result of a sum of two antiphase vectors is nearly zero, resulting in oscillation loopback gain less than unity.

In order to depict that, one can imagine the oscillator as being composed of ideal voltage-controlled current sources and phase shifters (see Fig. 2). Two active devices act antiphase if the phase shift β becomes

$$\beta = \pi/(2|r - s|) \tag{2}$$

where r and s stand for active section position. Critical β values are tabulated in Table I.

Now, let us consider phase shifts β for different frequencies. Let us assume ideal active devices possessing a phase shift Φ of π radians. One can find the phase shifts for devices biased into the active region one at a time. These shifts are tabelated at Table II.

TABLE I
CRITICAL PHASE SHIFTS BETWEEN rth AND sth TRANSISTORS

r - s	1	2	3	4	5	6	7	8
no. of β	2	4	6	8	10	12	14	16
β_c [deg]	90	45	30	22,5	18	15	12,9	11,25

TABLE II
PHASE SHIFTS REQUIRED FOR DIFFERENT FREQUENCIES

n	1*	2*	3*	4	5*	6	7	8	9*
no. of β	1	3	5	7	9	11	13	15	17
β_n [deg]	180	60	36	25	20	17	14	12	11
ω_n / ω_0	1	0,5	0,31	0,22	0,17	0,15	0,12	0,1	0,09

It is important to mantain active devices in first oscillator stages, while some stages providing for lower frequencies could be left without an active device (e.g., composed solely of inductors and capacitors). In the case of a decade bandwidth distributed oscillator, computer simulations have confirmed that only sections denoted by an asterisk in Table II should contain active devices.

Tuning between two frequencies could be achieved by a pair of transistors only if the tuning range required does not need in β causing antiphase operation. This effect is always encountered between first and second FET's at $0.7f_c$ (critical frequency of artificial transmission line). The problem can be solved by an additional FET connected between the first and the second sections, as depicted in Fig. 1.

The oscillation frequency can be predicted using computer-aided design (CAD) techniques as a function of active FET positions and differential transconductances. This tuning function depends on the type of artificial transmission line section used. The tuning function prediction provides for g_m (differential transconductance) required from each pair of FET's. The tuning function is called here a "linear" function because it is derived from linear (small-signal) parameters of the FET.

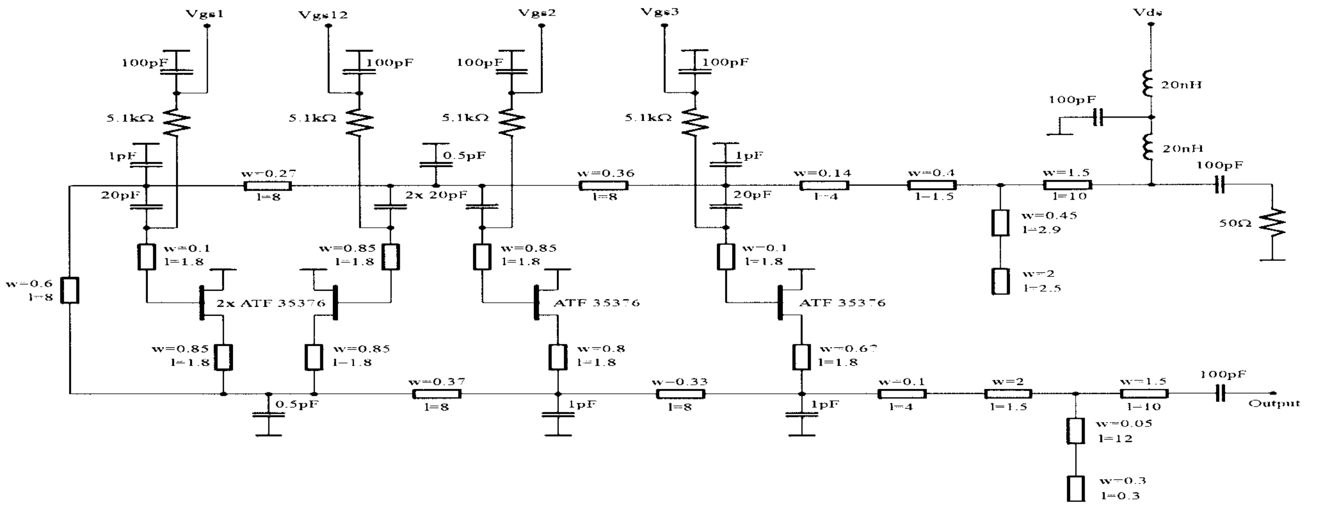

Fig. 3. Simplified schematic diagram of the oscillator. Line dimensions are in millimeters.

III. Experimental Realization of the Distributed Oscillator at 4 GHz

As we learned from [2] and subsequent analyses, there are several important goals to keep in mind in order to design a good distributed oscillator.

- A good match should be achieved, both in drain and gate lines. The match should be better than −20 dB over the tuning range. (Otherwise, parasitic oscillations occur.)
- The artificial lines should form a low-pass filter. (Otherwise, the spectral purity of the output signal suffers.)
- Introducing the transistor between the first and second stage is a crucial point.
- The artificial transmission line should be composed of M-derived sections.
- The design should take into account nonlinearities in the circuit in order to develop a suitable tuning function.

Periodically loaded transmission line concept [3] was found suitable to achieve these goals.

In order to test the idea of a distributed oscillator at microwave frequencies, we have chosen a frequency of approximately 4 GHz. The choice has been predetermined by the fact that this frequency is high enough for all circuit parameters to be in effect yet low enough to allow for use of packaged devices. The design has been enabled by the results obtained with our last distributed oscillator design at 100 MHz [2] and facilitated by a number of computer simulations, both linear and nonlinear. We decided to build a three-stage four-active-device oscillator. This decision has been affected by the following reasons.

- The most difficult point is in connecting the cross-coupled device between the first and second stages. This was therefore found to deserve experimental verification.
- A three-stage oscillator is capable of a tuning range of about 1–3.
- Wider tuning ranges result in operation below the critical frequency of the artificial line and therefore in worse spectral purity.
- 4 GHz is the limit that could be reached using packaged devices, yet the frequency is high enough for all effects to come into consideration (our previous design at 100 MHz has been simplified by the fact that artificial lines have been formed by lumped capacitors that were large enough—bias variations of active device parameters had no effect on mismatch).

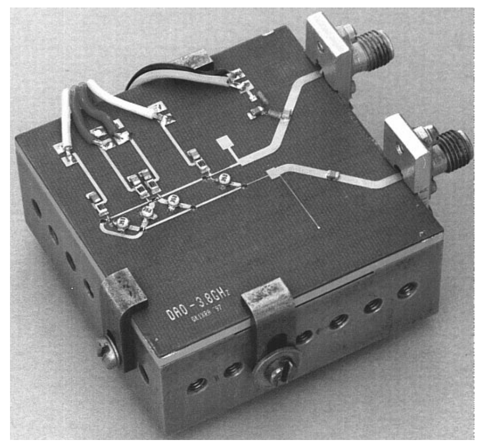

Fig. 4. Photograph of a real sample of the oscillator at 4 GHz. Dimensions of the board are 50 × 50 mm.

In the design, frequency-lumped elements (inductors and FET's) exhibit considerable parasitic elements values, some of which are bias-dependent. These parasitic elements must be accounted for during design. Periodically loaded transmission lines and M-derived sections were used. As to circuit layout, the cornerstone is found in connecting the FET between the first and second stages. Proper line lengths should be maintained, while the imedance-matching demands imposed by the first and second stages are somewhat contradictory. The cross-coupled device adds gate capacitance to the second stage, but drain capacitance to the drain line makes broad-band matching more difficult.

The oscillator is a nonlinear device. After attempting to carry out its simulation in the latest microwave CAD packages, we have to resource to time-domain analysis. The results of numerous simulations [4] gave the information necessary for tuning prediction.

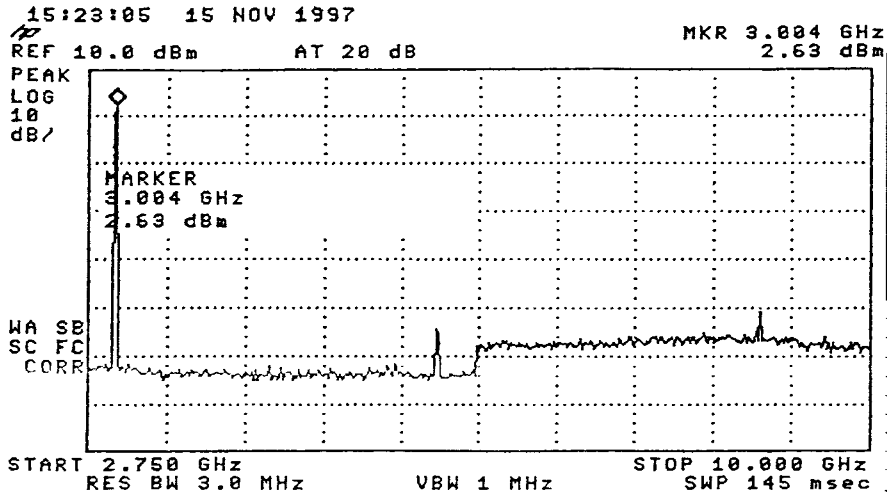

Fig. 5. An example of measured output spectrum of the oscillator depicted in Figs. 3 and 4. Gate bias voltages are set for oscillation at 3 GHz.

IV. Realization of the Distributed Oscillator

The oscillator consists of three sections with four FET's. The FET is a pHEMT ATF35376 that has good gain and minimal values of parasitic elements. The oscillation frequency is controlled by a change of gate bias voltages. The critical frequency of the oscillator is 3.8 GHz. The artificial transmission line is realized as M-derived sections of a periodically loaded transmission line with added capacitors. The oscillator is matched by half of an M-derived section realized with distributed elements. The gate bias filters are realized with high impedance on the output of the filter and composed of a resistor and a shunt capacitor. The drain bias filter is realized with the same goals as an *LC* T-network, and each FET drain is biased through the artificial transmission line. This experimental sample of the oscillator has made use of planar technology with MIS capacitors where needed. The oscillator is realized on a 0.5-mm-thick substrate with $\varepsilon_r = 2.33$. A low dielectric constant allows for a relatively large circuit. The topology and layout are shown in Fig. 3. A photo of the oscillator can be seen in Fig. 4.

V. Results

The oscillator is working well, meeting design goals. The tuning range is 1–3.5 GHz with output power 3–11 dBm. The oscillator has very good spectral purity, as shown by the arrow spectral line, and very good supression of second and third harmonics (see Fig. 3). The level of second-harmonic frequency ranges from -44 to -18 dB. A supression of about -35 dB is achieved at frequencies over $f_c/2$ (second harmonic) or $f_c/3$ (third harmonic), where second (third)-harmonic frequency is not propagated. The third-harmonic frequency is mantained from -55 to -17 dB. A sample of output spectrum can be seen in Fig. 5.

VI. Conclusion

The idea of a distributed oscillator has been found viable in the microwave region. The oscillator is instantly tunable, and the output signal harmonic purity is comparable to other tunable oscillator arrangements in use. The oscillator is suitable for MMIC technology. Wide tuning ranges could be achieved if more stages were added.

References

[1] Z. Škvor, S. Saunders, and C. S. Aitchitson, "Novel decade electronically tuneable microwave oscillator based on the distributed amplifier," *Electron. Lett.*, vol. 28, no. 17, pp. 1647–1648, Aug. 1992.
[2] L. Divina and Z. Škvor, "Experimental verification of a distributed amplifier oscillator," in *Proc. 25th EuMC 1995 Conf.*. Kent, U.K.: Nexus Media Limited, 1995, pp. 1163–1167.
[3] T. T. Y. Wong, *Fundamentals of Distributed Amplification*. London, U.K.: Artech House, 1993.
[4] L. Divina, "On a distributed amplifier oscillator," in *COMITE 1997*, vol. 1, Czechoslovakia Section IEEE, Pardubice 1997, pp. 33–36.
[5] Hewlett-Packard, SeriesIV 6.5 PC User Guide.
[6] L. Divina and Z. Skvor, "The distributed oscillator at 4 GHz," in *Int. Microwave Symp. Dig.*, Baltimore, MD, 1998, pp. 865–868.
[7] R. S. Pengelly, *Microwave Field-Effect Transistors—Theory, Design and Application*, 2nd ed. London, U.K.: Research Studies Press, 1986.

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