A 6 GHz high power and low phase noise VCO using an InGaP/GaAs HBT

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Abstract: A 6 GHz voltage controlled oscillator (VCO) optimized for power and noise performance was designed and characterized. This VCO was designed with the negative-resistance (Neg-*R*) method, utilizing an InGaP/GaAs hetero-junction bipolar transistor in the negative-resistance block. A proper output matching network and a high *Q* stripe line resonator were used to enhance output power and depress phase noise. Measured central frequency of the VCO was 6.008 GHz. The tuning range was more than 200 MHz. At the central frequency, an output power of 9.8 dBm and phase noise of –122.33 dBc/Hz at 1 MHz offset were achieved, the calculated RF to DC efficiency was about 14%, and the figure of merit was –179.2 dBc/Hz.

Key words: VCO; C-band; InGaP/GaAs HBT; low phase noise; high power; efficiency
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1. Introduction

High performance frequency sources are very important in wireless communication systems, and oscillators are essential parts of them. Most systems need frequency variable oscillators such as VCOs whose oscillation frequency can be tuned by a control voltage. Much attention had been devoted to the phase noise performance of oscillators in the past, while output power and efficiency were not concerned with much. Usually, power was coupled out of the oscillator core slightly, mostly by small capacitors, even attenuators. A buffer stage after the oscillator core was always needed to get enough power and avoid heavy load. Since power is precious and more stages lead to more parasitic problems and risks in circuit design at high frequency, the high power and low phase noise oscillator core make it predominant in applications, especially where cost, power consumption and reliability are important. In recent years, some researches on oscillator power were carried out[1−3]. By introducing a power matching method into oscillator design, high power and efficiency were achieved but harmonics and noise rose at the same time.

In this paper, a 6 GHz VCO was made with a high output power for direct use without a buffer stage. At the same time, harmonics and noise were kept suitably low. For this purpose, a load matching network was designed for power coupling, and the resonator was mainly constructed by micro-strip lines to obtain high quality factor (*Q*). Design optimizations of the load and resonator were made carefully, and an acceptable result was achieved. The measured efficiency of 14% was quite high compared to the domestic results ever reported, which were mostly below 5%. At the same time, the phase noise was kept lower than –115 dBc/Hz at 1 MHz offset, which was also a nice value for high power X-band oscillators. On the other hand, some tuning range was sacrificed to get the good power and noise performance.

2. Negative-resistance oscillation theory and circuit optimization

Microwave oscillators are often designed by a Neg-*R* method with which dealing with the complicated parasitic effects can be avoided and powerful CAD tools can be used to build an oscillation easily. In the Neg-*R* method, scatter parameters and port impedance are mainly considered. A block diagram of a Neg-*R* oscillator is shown in Fig.1. An active device with a proper positive feedback gives a reflection coefficient of $\Gamma_a > 1$ and a port impedance with a negative real part.

To keep a stable oscillation, the energy loss of the resonator should be compensated by the Neg-*R* block, so mathematically the following conditions should be satisfied[4, 5]:

$$\Gamma_a \Gamma_{res} = 1 \tag{1}$$

$$\begin{cases} R_a + R_{res} = 0, \\ X_a + X_{res} = 0. \end{cases} \tag{2}$$

To start an oscillation, a margin is needed as Eq.(3),

$$\begin{cases} \Gamma_a \Gamma_{res} > 1, \\ R_a + R_{res} < 0, \\ X_a + X_{res} = 0. \end{cases} \tag{3}$$

Although it is controversial on the Neg-*R* design method around its output power and phase noise prediction ability, high *Q* factor and proper impedance matching network are still the silver bullet for engineering, even they are not as precise as those in the traditional feedback loop design method that can analyze the power and noise systematically[6]. Much attention was paid to the *Q* and load matching in this design.

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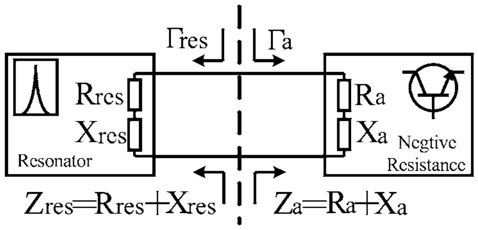


Fig.1. Block diagram of a negative-resistance oscillator.

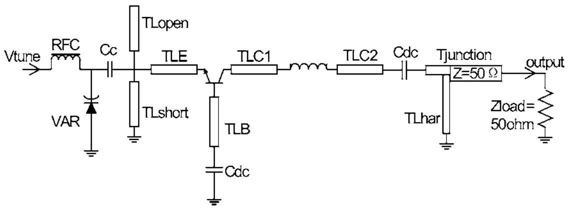


Fig.2. Schematic of the oscillator.

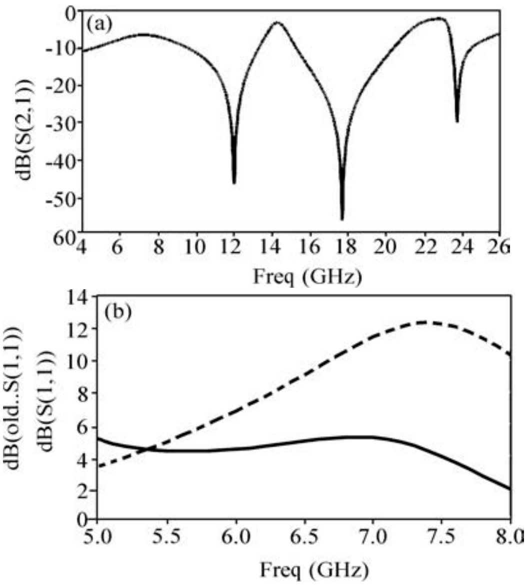


Fig.3. (a) S_{21} of the load matching network; (b) S_{11} of the Neg-*R* block with (the solid line) and without (the dashed line) the load matching network.

The oscillator was designed with the Neg-*R* method mentioned above, and simulated in Agilent Advanced Design System (ADS). The schematic of the oscillator is shown in Fig.2, in which the bias network is omitted. An InGaP/GaAs HBT was employed as the active device due to its low $1/f$ noise[7] and good power performance. The HBT was used in common-base configuration to make the oscillation start more easily.

To get more output power from the oscillator core, the load needs to be coupled tightly, while more frequency pulling will be induced inevitably. The sensitivity to the load variation can be reduced by using a high impedance load. While designing the load network, less lumped components requirement, lower harmonics and flat amplitude of the Neg-*R* block S_{11} were all taken into consideration. Micro-strip lines TLC1, TLC2, TLhar and the small inductor together with DC block capacitors and DC feeding lines made up the load network that converted the load impedance higher and fulfilled the phase matching. Since high power leads to more harmonics, DC feeding lines and TLhar were utilized to restrain the high order harmonics instead of a low pass filter (LPF) with which more lumped components were needed. Figure 3 shows the simulation result, and the S_{21} of the matching network in Figure 3 (a) shows good attenuation to the 2nd and 3rd harmonics at the frequency of 12 and 18 GHz. The simulated S_{11} of the Neg-*R* block with (the solid line) and without (the dashed line) the load matching network is shown in Fig.3 (b). With the load matching network, the amplitude of S_{11} was flattened effectively and set to a proper value that gave a low but enough gain, leading to an operation of less nonlinearity.

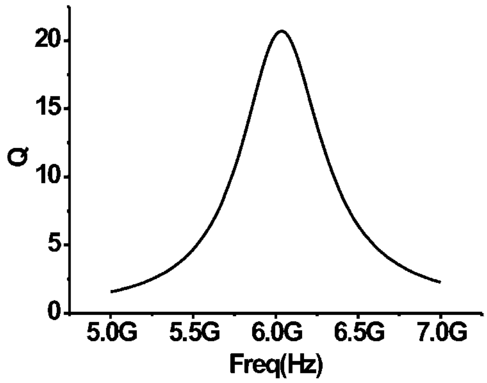


Fig.4. Evaluation of load Q.

Although the load Q of the circuit is hard to predict by the Neg-*R* method, a larger slope of the resonator reflection phase or the reactance may lead to a higher load Q. An evaluation of load Q from the group delay of S_{11} is shown in Fig.4, and a Q of about 20 at 6 GHz was achieved. It needs to be pointed out again that the Q is not a precise but effectively estimated value that can be used for the resonator optimization. The operating frequency and the resonator Q were mainly determined by the micro-stripe line TLopen and TLshort. A SMV1232 abrupt diode varactor from Skyworks is connected through the small coupling capacitor Cc for tuning. The TLE that serves as phase shifter and impedance converter also affects the frequency and Q. By regulating the lengths and widths of the three segments of micro-stripe lines, there are six independent parameters that can be used to tune the resonated frequency and Q at the required frequency conveniently. By tuning the resonator in this way, a simulated phase noise of -120 dBc/Hz at 1 MHz frequency offset was achieved. The circuit was simulated by the harmonic balance and transient simulator, and the micro-stripe lines were simulated and adjusted by Momentum simulator, the 2.5D E-M tools in ADS.

3. Circuit realization and testing

The VCO was built on a Taconic PTFE board. The photograph of the circuit with a fixture is shown in Fig.5, and the inserted picture at the right-top is the mounted HBT. The HBT was biased at V_{ce} = 4.2 V and I_c = 16 mA, and showed a f_t about 27 GHz and f_{max} more than 40 GHz, which is quite adequate for this application.

The VCO was measured on an HP 8563E spectrum

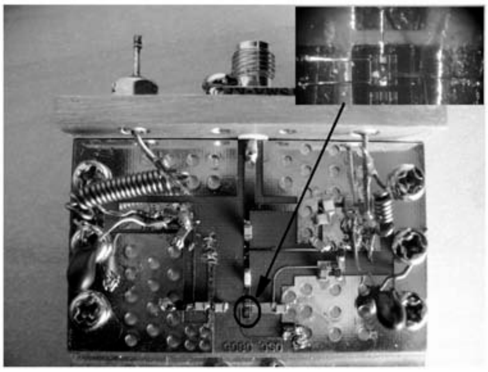
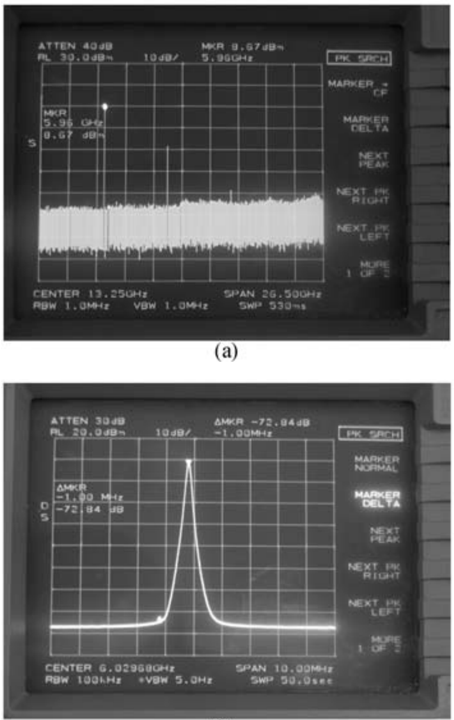


Fig.5. Photograph of the oscillator circuit.



(a)

(b)

Fig.6. (a) Output spectrum ($V_{\rm tune}$ = 3 V, MKR: 5.96 GHz, 8.67 dBm); (b) Phase noise testing ($V_{\rm tune}$ = 3 V, MKR: −1.00 MHz, −72.84 dB).

analyzer. After frequency adjusting, an oscillation at 6.008 GHz was achieved at 4 V tuning voltage. The photographs of measuring output spectrum and phase noise were shown in Fig.6. A clear spectrum was obtained as shown in Fig.6 (a), in which the 2nd and the 3rd harmonic are lower than −23 and −40 dBc without any load matching network adjusting. This result is acceptable for the oscillator without output LPFs.

Figure 6 (b) is the photograph of phase noise tested with a 10 MHz frequency span and 100 kHz RBW of the spectrum analyzer. At the central frequency 6.008 GHz, the VCO output power was 9.8 dBm. With this spectrum analyzer HP8563E, the phase noise and FOM can be calculated from Eqs.(4) and (5)[8].

$$\mathrm{PN}(f_{\rm offset}) = \mathrm{PowerDelta(dB)} - 10\lg(\mathrm{RBW}), \qquad (4)$$

$$\mathrm{FOM} = \mathrm{PN}(f_{\rm offset}) - 20\lg\frac{f_0}{f_{\rm offset}} + 10\lg\frac{P_{\rm DC}}{1\mathrm{mW}}, \qquad (5)$$

where the PowerDelta is the power at a frequency offset proportion to the carrier power in dB, which can be read out directly from the spectrum analyzer. The RBW is the operating resolution band of the spectrum analyzer. From the measured data, the single sideband phase noise was –122.83 dBc/Hz at 1 MHz and –101.67 dBc/Hz at 100 kHz frequency offset. The measured noise performance met the simulation result very well, indicating that the Q optimization method was quite reasonable. FOM was calculated to be –179.2 dBc/Hz.

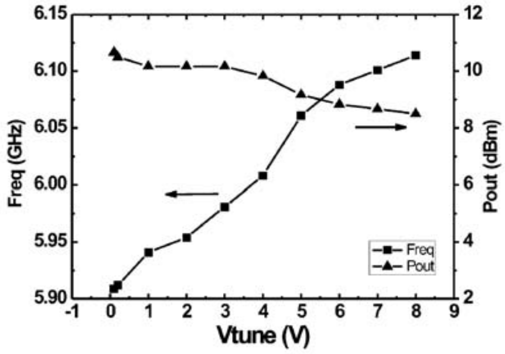


Fig.7. Frequency and power tuning.

With the control voltage tuning from 0.1 to 8 V, the frequency of the VCO shifted from 5.908 to 6.114 GHz, the output power varied from 8.5 to 10.5 dBm, and the worst phase noise at 1 MHz frequency offset was –116 dBc/Hz. These results were adequate for most common applications' requirement. The measured tuning characters of power and frequency are shown in Fig.7.

4. Conclusions

A high power and low noise VCO without buffer stage was realized. The 6 GHz VCO was built with only one InGaP/GaAs HBT as active device, using micro-stripe line resonator on PTFE board. By introducing a load matching network and a resonator Q optimization method, the VCO shows good performance of high power and low phase noise. Measured operating frequency was 6.008 GHz with a tuning range of more than 200 MHz. The output power at central frequency was 9.8 dBm with a DC to RF efficiency of 14%. The measured phase noise was –122.83 dBc/Hz at 1 MHz frequency offset and the calculated FOM was –179.2 dBc/Hz. The measured performance met the target of design very well and the optimization method was proved to be effective.

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