A Dual-Band (13/22-GHz) VCO Based on Resonant Mode Switching

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***Abstract*—A dual band voltage-controlled oscillator (VCO) that can cover 13- and 22-GHz bands is proposed and implemented using an InGaP/GaAs heterojunction bipolar transistor (HBT) technology. The frequency band is selected by mode switching between differential mode at low frequency and common mode at high frequency. The differential mode means that voltages appearing at two tank ports have opposite polarities and the common mode, the same polarities. Mode switching allows the VCO to operate at two resonant frequencies with a single LC tank. The measured phase-noise performances of a dual band VCO are −108 and −106 dBc/Hz at 1 MHz offset at the frequencies of 13 and 22 GHz, respectively, while drawing 22 mA and 16 mA from a 4-V supply. Switching times between two bands are less than 24 ns.**

***Index Terms*—Balanced topology, dual band, InGaP/GaAs HBT, mode switching, VCO.**

I. Introduction

The monolithically integrated multiband voltage-controlled oscillator (VCO) remains a challenging problem, since easy and fast band switching capability is difficult to be implemented. There have been two means to switch. One is a regenerative multiplication method, in which a frequency divider or a multiplier is used to obtain another band other than fundamental band of a given VCO [1], [2]. The frequency band is determined by dividing or multiplying ratio. However, this entails additional circuitries that are not used to generate a carrier signal, causing large power consumption. The other is a switched-capacitor method, which is more frequently used in lower frequency than GHz-regime [3], [4]. It employs a capacitor with a series connected switch, which controls the capacitance of a LC tank. In this case, the parasitic resistance of the switch degrades the quality factor of the LC tank. This becomes serious as operating frequency increases. As a consequence, phase noise performances are deteriorated. While parasitic resistance decrease with larger switch, the parasitic capacitance of the switch also increases to reduce switching frequencies.

In this letter, a novel dual band VCO structure is proposed, where a balanced VCO core with buffer amplifiers oscillates in differential mode as well as in common mode. The mode is selected by switching current sources.

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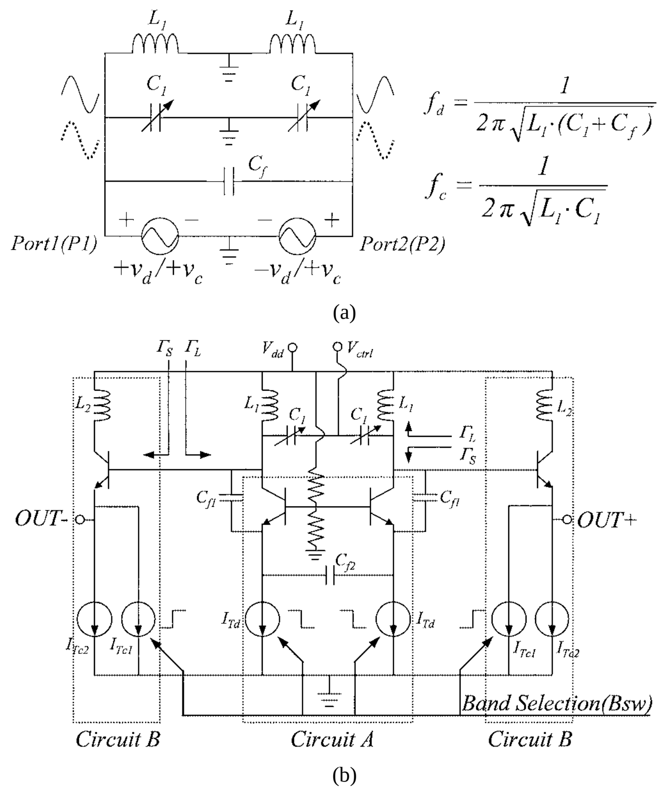

Fig. 1. (a) Mode switching concept. (b) Schematic of a dual band VCO circuit.

II. Dual Band Configuration

Fig. 1(a) depicts a mode-switching concept. When differential signals (v_d) are applied to LC-tank, the resonant frequency (f_d) is determined by L_1, C_1 and C_f. On the other hand, when common mode signals (v_c) are applied, the resonant frequency (f_c) is set by only L_1 and C_1, because port 1 and 2 have same potential and C_f does not affect on resonant frequency. By switching these, one can make an oscillator with a single LC-tank have two different resonant frequencies. The circuit schematic of a dual band VCO is shown in Fig. 1(b). It is composed of two negative-resistance generators (Circuit A, B) and one LC tank. Here, varactors are used for frequency tuning not for band switching. The mode switching is accomplished by controlling current sources.

When band-selection signal $(B_{\rm sw})$ is on, the balanced VCO core (circuit A) generates negative resistance, which compensates the loss of tank. It creates differential outputs and results in oscillation at low frequency band. Circuits Bs are used as output buffers, where $I_{\rm Tc1}$ is zero. In this mode, two common-base Colpitts VCOs are synchronized through base terminals and capacitors C_{f2}[5]. The negative resistance is mainly determined

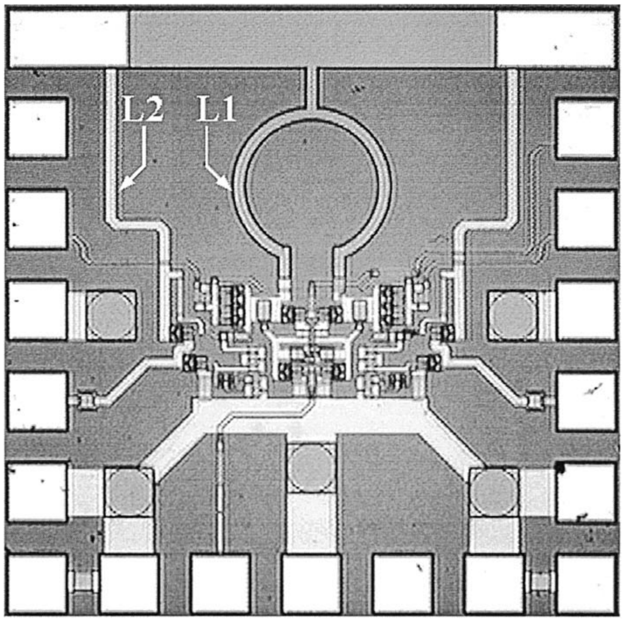

Fig. 2. Photograph of a fabricated dual-band VCO (1×1 mm^2).

by feedback capacitors C_{f1} and C_{f2}, which are optimized to achieve the maximum negative resistance. The oscillation frequency is given by

$$f_c = \frac{1}{2\pi\sqrt{L_1 \cdot \{C_1 + C_{f1} \parallel (C_{f2} + C_{be})\}}}. \tag{1}$$

When $B_{\rm sw}$ is off, the tail currents of Circuit A, $I_{\rm Td}$ decreases to 0 mA and the currents of Circuit B increase two times. Circuit B generates negative resistance with an aid of L_2. Two identical Circuits Bs operate with same phase, generating common-mode outputs. Two tank voltages are coupled to match the phases of two common mode VCOs through feedback capacitors C_{1f} and C_{2f}. The output signals are collected in emitters. The oscillation frequency is estimated by

$$f_d = \frac{1}{2\pi\sqrt{L_1 \cdot C_1}}. \tag{2}$$

However, in a real situation, the operating frequency is affect by parasitic capacitances, inductances, and the quality factor of the LC-tank. The oscillation frequency could be accurately estimated by small signal analysis of Agilent ADS with the condition of

$$\Gamma_S \cdot \Gamma_L = 1. \tag{3}$$

The dual-band VCO is fabricated with an InGaP/GaAs HBT technology, which offers n-p–n HBTs with an f_T of 30 GHz, nitride MIM capacitors, TaN resistors, and two metal layers. The thicknesses of two metal layers are 1 μm and 1.3 μm, respectively. Inductors are implemented using 75-Ω microstrip lines, where one metal layer is stacked on the other metal layer and base-collector junction capacitors are used for varactors. The photograph of a fabricated VCO is shown in Fig. 2. The layout was made as symmetrical and compact as possible to ensure differential operation and to lower parasitic capacitances and inductances in interconnecting lines.

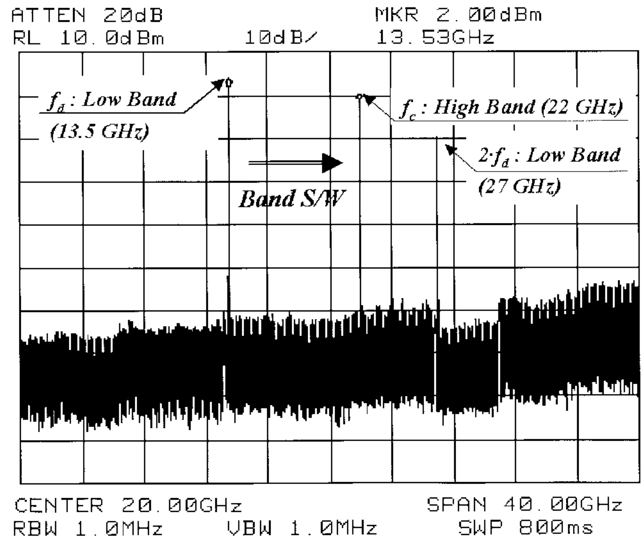

Fig. 3. Output spectrum of a dual band VCO with band switching.

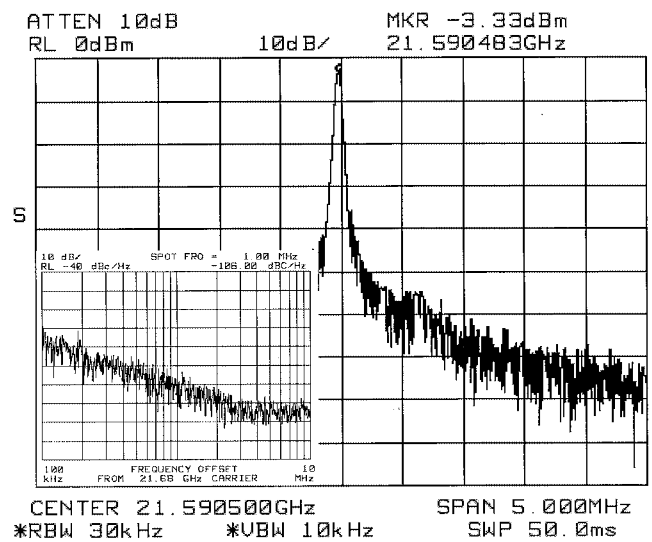

Fig. 4. Output spectrum of the VCO at 21.6 GHz and phase noise measurement (inset).

III. Experiment Results

On-wafer measurements of output spectrums and phase noise performances were obtained using an Agilent 8764E spectrum analyzer and its phase noise measurement kit. Fig. 3 shows the overlapped spectrum of low and high frequency band outputs. The VCO creates differential outputs at the frequency (f_d) of 13.5 GHz and common-mode outputs at the frequency (f_c) of 22 GHz from a 4-V supply. The mode-selection bias $(B_{\rm sw})$, which controls current sources, selects operation mode and frequency band. $B_{\rm sw}$ for low band mode is $\sim$2.4 V. And *Bsw* for high band mode is between 0 and 1.4 V. At the low band mode, the bias current of the balanced core (*Circuit A*) is 7 mA and that of the buffers (*Circuit Bs*) is 8 mA. But at high band mode the balanced core is in cutoff state and the current of Circuits B increases to 16 mA, which generates negative resistance. When the mode-selection bias is over 1.9 V, only differential mode signal at 13 GHz is observed, and below 1.4 V, only common mode signal at 22 GHz is obtained. Between them, two mode

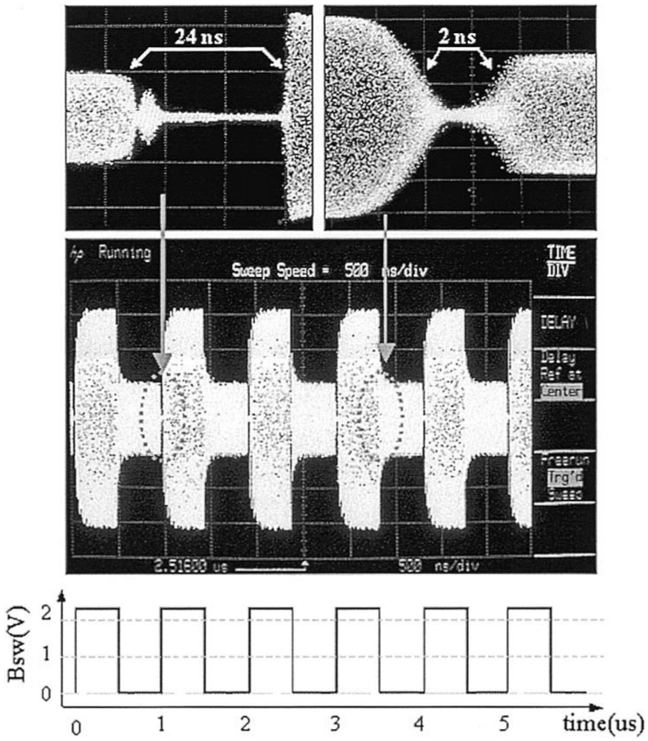

Fig. 5. Band-switching behaviors of a dual band VCO in time domain.

frequencies appear at the same time and the mixing components of 13 and 22 GHz also appear. The VCO provides 2-dBm outputs with tail currents, $2 \cdot I_{\rm Td}$ of 7 mA in low-frequency band. The tail currents are optimized for low phase noise performance. The phase noise at this bias condition is -108 dBc/Hz at the 1-MHz offset frequency. Fig. 4 shows the output spectrum and the phase noise spectrum in high frequency band, which shows -1 dBm output and phase noise performance of -106 dBc/Hz at the 1-MHz offset frequency. The VCO at high band mode draws 16 mA.

The measurement of VCO's waveforms is not easy due to high operating frequency and the reason that it is difficult to extract triggering signal from a free running VCO. Thus, we wanted to show only band switching operation, here. Only the frequency-selection was measured using a sampling oscilloscope. The band-selection bias $(B_{\rm sw})$ of a 1-MHz rectangular signal is created by a pulse generator and fed back to the triggering signal input of the sampling oscilloscope. Fig. 5 shows the periodic band switching operation in time domain between low- and high-frequency band. Clear switching operation is observed. When $B_{\rm sw}$ is 2.4 V, a 13-GHz carrier is generated and switched to 22 GHz at the $B_{\rm sw}$ of 0 V. Upper two figures in Fig. 5 gives enlarged views at each switching time between

TABLE I
SUMMARY OF THE DUAL BAND VCO PERFORMANCES

Parameters \ Performance	Dual Band VCO	
	Low Band	**High Band**
Supply Voltage	**4 V**	
Current Consumption		
- Differential Mode	**3.5 (Core), 4 mA(Buffer)/per side**	
- Common Mode	**8 mA /per side**	
Chip size	**1 × 1 mm²**	
Frequency (GHz)	**13.2 ~ 13.8**	**21.8 ~ 22.2**
Output Power(dBm)	**2**	**-1**
Phase Noise @ 1 MHz	**-108 dBc/Hz**	**-106 dBc/Hz**
Swithing time(ns)	**4 (H →L)**	**24 (L →H)**
F.O.M (dBc/Hz)	**-176**	**-175**

high and low frequency band. The band switching time from high to low frequency band is about 20 ns, which are somewhat longer than the simulated result, 6 ns. This is expected to be due to the inductances of bias-feeding lines in measurement setup and the rising time of band-switching signal. Nonetheless, the switching time was very short for the band selection. Table I summarizes the measured performances.

IV. CONCLUSION

A dual-band VCO that can select 13- and 22-GHz frequency bands is successfully realized with an InGaP/GaAs HBT foundry. It utilizes mode switching between differential and common-mode oscillations of a resonator. This intrinsically provides big frequency change with simple current control. The dual-band VCO shows fast band-switching times of 20 and 4 ns between low to high and high to low band frequencies, respectively. The VCO shows phase noises performances of -108 and -106 dBc/Hz at 1-MHz offset frequency for 13 and 22 GHz, respectively, drawing 22 mA and 16 mA from a 4-V supply.

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