A mm-Wave Arbitrary 2^N Band Oscillator Based on Even-Odd Mode Technique

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***Abstract* — A technique to build mm-wave arbitrary 2^N band oscillators is presented. Based on even-odd mode operation, the technique breaks the fundamental tradeoff between frequency switching range and tank quality factor, Q, which exists in classical switched-capacitor and switched-inductor methods. As a result, this technique achieves multi-band operation with FOMs comparable to single band oscillators. To verify the theory, a quadruple band oscillator with 4 arbitrary chosen frequencies (43, 49, 58 and 75 GHz) is implemented in 65-nm CMOS technology. The phase noise measurements taking at 1 MHz offset are -100.3, -95.3, -93.8 and -86.2 dBc/Hz, respectively. The power consumption of the oscillator core is 12mW. The presented technique would enable the development of mm-wave software-defined multi-standard radios.**

***Index Terms* — mm-wave, multiband, quadruple band, even-odd mode, oscillator, VCO, 60 GHz, software-defined radio, CMOS.**

I. Introduction

Driven by software-defined multi-standard radios, for frequency below Ku band, many VCO multiband techniques have been presented [1]-[4]. However, such techniques have not been applied to mm-wave frequencies. Recently FCC released several mm-wave licensed and unlicensed bands to fulfill increasing demand for multi-Gb/sec data transmission. For example, there are licensed bands at 71-76, 81-86 and 92-95 GHz, which are open for high-speed, point-to-point wireless local area networks. Furthermore, an unlicensed band at 57-64 GHz has caught attention from both academia and industry. In addition, the 40.5-43.5 GHz band is used for local multipoint distribution services. Therefore, it is expected that a need for a frequency source that can cover all or a substantial part of these bands will emerge in the future. Classically, implementing such a source is done by multiplexing several sources on-chip [5], [6]. At mm-wave frequencies, however, the multiplexer (MUX) itself is required to operate over an ultra-wide frequency range. Such a design consumes excessive area and power. The MUX can be avoided if the oscillator employs a single tank with multiple resonant modes.

For frequencies below Ku band, the switched-capacitor and switched-inductor methods are the most common [1]. However when using these methods at mm-wave frequencies, a large tuning range corresponds to excessive switch loss, and a resultant degradation in the Q of the LC tank. An alternative is the coupled inductor method [2], [3], however, for N bands, there are N-choose-2 (C_2^N) inductor coupling factors, k, that need to be carefully specified. For example, a 4-band oscillator requires 4 coupled inductors and needs 6 individual k-factors to be set. Designing such a passive structure with a limited number of good conducting layers in CMOS is difficult. In [4], Goel and Hashemi present a dual-resonance oscillator composed of two LC tanks in series. While the topology cleverly avoids Q-degradation due to switch loss, the resistance and parasitic capacitance of series non-oscillating tank can be problematic; as mentioned in [4], asymmetric waveforms, increased flicker noise and a small reduction in the Q of the LC tank can be expected. As the number of bands increases, the number of series LC tanks also increases, and these issues become more serious. Another approach is the dual-band oscillator that exploits left-handed material (LH) [7]. But, to expand this approach to N bands, $2\cdot(N-1)$ inductors are required, i.e., 6 inductors for 4 band. Furthermore, for N larger than two, in N-cell LH ring resonator, it is very challenging to switch between various equal phase node sets with $2n\pi/N$ phases to deliver the desired modes, where n=0, -1 … -(N-1). To resolve the problems, we present the simple even-odd mode 2^N band technique without the previous issues. And the technique requires only one inductor per tone.

II. Even-Odd Mode Multiband Technique

A. Fundamental Even-Odd Mode Block

Fig.1 shows a coupled transmission line and its equivalent capacitance network [8]. With the assumption of TEM propagation, two special types of excitation, even- and odd-mode, have been studied in literature as shown in Fig. 2. With even-mode excitation, the voltages on the strip conductors are in phase and equal in amplitude, which leads to the equivalent capacitor

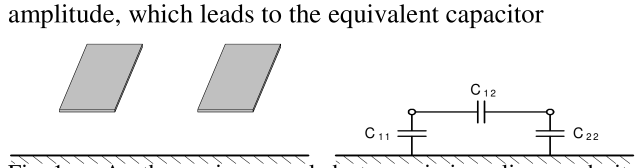


Fig. 1. A three-wire coupled transmission line and its equivalent capacitance network.

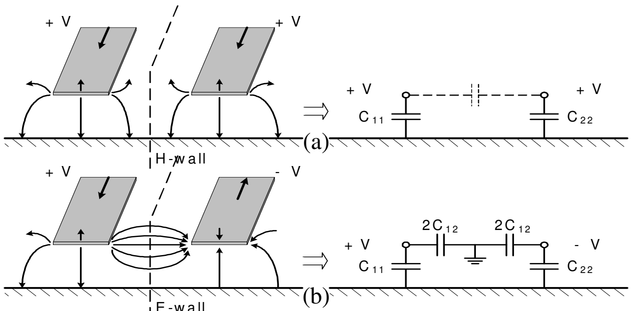


Fig. 2. Even- and odd-mode excitations for a coupled line, and the resulting equivalent capacitance networks. (a) Even-mode excitation. (b) Odd-mode excitation.

network shown in Fig. 2(a), where C_{12} is effectively open-circuited. On the other hand, for the odd mode, the voltages on the strip conductors are 180° out of phase and equal in amplitude, which leads to a virtual ground plane in between the two strip conductors. Hence each of the strips is effectively connected to the virtual ground by $2C_{12}$.

Following this concept, we can create the fundamental even-odd mode building block: a differential dual band even-odd mode resonator, as shown in Fig. 3. One can understand Fig. 3(a) as two LC tanks connected to each other by two C_1 capacitors. Fig. 3(b) and 3(c) show the differential even- and odd-mode resonance equivalent circuits, respectively, where "differential" refer to the voltages across each of the LC tank resonate differentially. Since the two LC tanks are identical, the resonant voltages are equal in amplitude. For even mode, the two LC tanks resonate in phase and C_1 is effectively open-circuited. On the other hand, for odd mode, the two LC tanks resonate 180° out of phase. Hence, each end of each LC tanks is effectively connected to the virtual ground by $2C_1$. The two resonant frequencies are $1/\sqrt{LC}$ and $1/\sqrt{L(C+C_1)}$. These are the only two modes that the resonator can support.

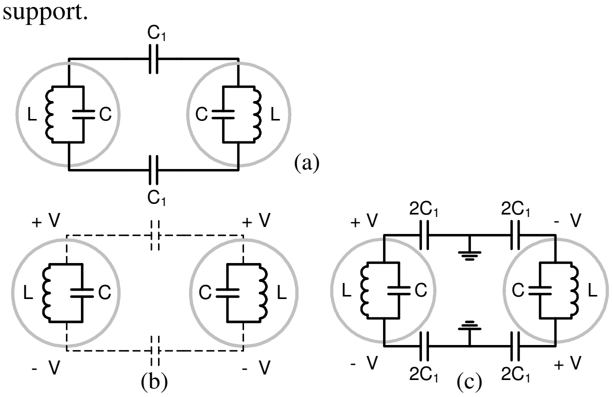


Fig. 3. Differential dual band even-odd mode resonator (a) Schematic. (b) Differential even-mode resonance equivalent circuit. (c) Differential odd-mode resonance equivalent circuit.

B. 2^N band Even-Odd Mode Resonator

To build a 2^N band differential even-odd mode resonator, first simplify the schematic of Fig. 3 as Fig. 4, with each circle representing a LC tank. Since only two phases can exist, let us mark one as "plus" and the other, which is 180° out of phase with "plus", as "minus". The thick line in schematic 4(a) represents the two capacitors connected between two LC tanks in Fig. 3(a). The thick line in equivalent circuit 4(c) represents that each end of the LC tanks effectively sees $2C_1$ to virtual ground.

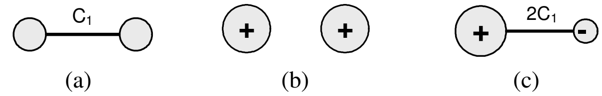


Fig. 4. Simplified schematic of Fig. 3 (a) Schematic. (b) Differential even-mode resonance equivalent circuit. (c) Differential odd-mode resonance equivalent circuit.

To expand the resonator from 2^{N-1} band to 2^N band, first, make a replica of a 2^{N-1} band resonator. Than connect the corresponding LC tanks of the two resonators by C_N capacitor pairs. By this method, Fig. 5 and Fig. 6 show a exemplary differential 4-band and 8-band even-odd mode resonators, respectively. The 4 resonant frequencies of the 4-band resonator are

$$1/\sqrt{LC},\ 1/\sqrt{L(C+C_1)},\ 1/\sqrt{L(C+C_2)},\ 1/\sqrt{L(C+C_1+C_2)}$$

The 8 Resonant frequencies of the 8-band resonator are

$$1/\sqrt{LC},\ 1/\sqrt{L(C+C_1)},\ 1/\sqrt{L(C+C_2)},\ 1/\sqrt{L(C+C_3)}$$
$$1/\sqrt{L(C+C_1+C_2)},\ 1/\sqrt{L(C+C_2+C_3)},$$
$$1/\sqrt{L(C+C_1+C_3)},\ 1/\sqrt{L(C+C_1+C_2+C_3)}$$

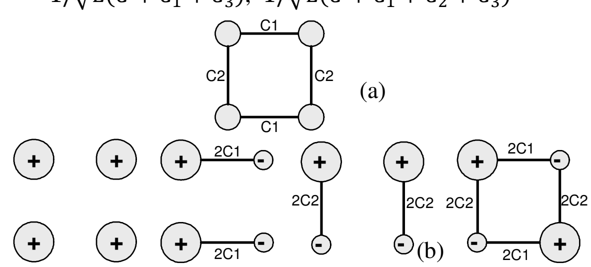


Fig. 5. Differential 4 band even-odd mode resonator (a) Schematic. (b) Equivalent circuits of 4 different modes.

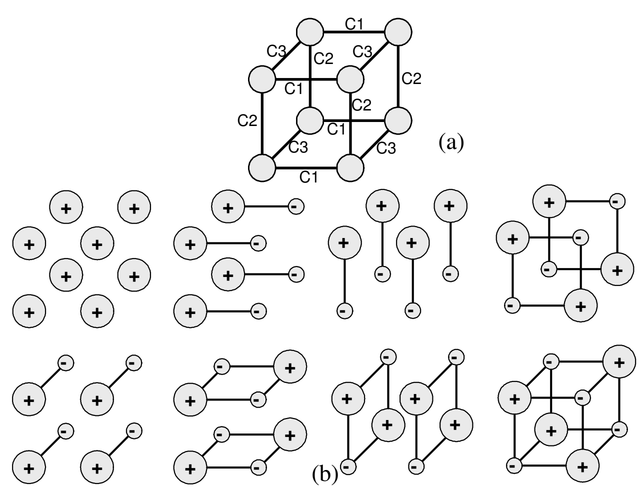


Fig. 6. Differential 8 band even-odd mode resonator (a) Schematic. (b) Equivalent circuits of 8 different modes.

To prove the 2^N inductor resonator has 2^N differential resonant frequencies, notice that each LC tank is connected to N other LC tanks through $C_1 \ldots C_N$ capacitor pairs. From even-odd mode analysis, each capacitor pair can either be seen or act as equivalent opened circuit. Thus the total number of combinations will be

$$C_1^N + C_2^N + \cdots + C_N^N = (1+1)^N = 2^N$$

An alternative way to think this is as follow. First, assume a 2^{N-1} inductor resonator have 2^{N-1} resonant frequencies, which is true for N=2. When we add additional C_N pairs to expand the resonator to 2^N inductor structure, all the combination of resonant frequencies of the 2^{N-1} resonator get another degree of freedom from C_N pairs, which offer 2 extra choice, even or odd mode. Thus the total number of resonant frequencies equals to $2^{N-1}x2 = 2^N$.

C. Even-Odd Mode Selecting Switch

To select the wanted mode, even-odd mode selecting switches are added to each of the C_N capacitor pairs, as shown in Fig.7. The switch set is compose of a pair of parallel switches, S_e, to select even mode and a pair of cross switches, S_o, to select odd mode. The switches S_e and S_o are operated complimentarily. Notice that once the wanted mode is selected, the voltages at the two ends of each "on" switch are the same in both phase and amplitude. Thus the switches are effectively open-circuited. Hence, they do not consume power, do not load the tank, and do not contribute noise. That is, the switches degrade the Q of unwanted modes, but do not affect the Q of the wanted mode.

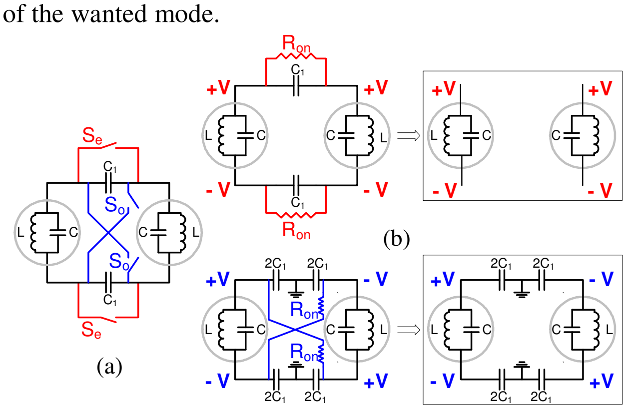


Fig. 7. Differential dual band even-odd mode resonator with complimentary mode selecting switches. (a) Schematic. (b) Differential even-mode equivalent circuit. (c) Differential odd-mode equivalent circuit.

III. MM-WAVE QUADRUPLE BAND OSCILLATOR

A quadruple band oscillator with the resonator in Fig. 5 and mode selecting units in Fig. 7 is implemented to verify the even-odd mode multiband technique, as shown in Fig. 8. The total parasitic capacitance each inductor sees is

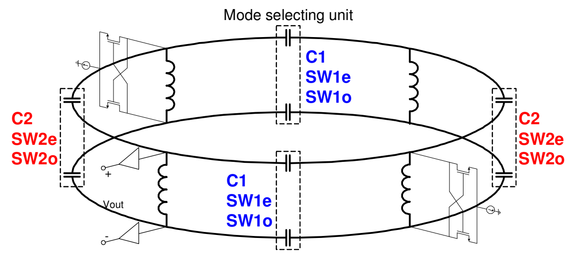


Fig. 8. Schematic of the quadruple band oscillator.

designed to match each other. Fig. 9 shows the large signal tank impedance (when driven with a 1.6V sine-wave) versus frequency under 4 different switch-set configurations. The small signal impedance of the switchless passive tank is also plotted for comparison. Notice that, even with this small switch size W/L=1/0.06μm, the quality factor of the wanted mode is well maintained in each plot. The impedance of the other tree unwanted modes is suppressed.

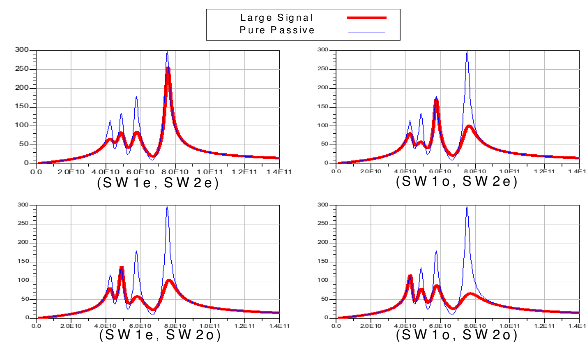


Fig. 9. Impedance of switchless passive tank vs large signal 1st harmonic impedance of the tank with W/L=1/0.06μm mode selecting switches over different turned-on switch set.

IV. MEASUREMENTS

The proposed quadruple band oscillator is implemented in a 65-nm CMOS process. The 4 arbitrary chosen frequencies were 43, 49, 58 and 75 GHz. The size of C_1, C_2 and L are 20fF, 38fF and 160pH, respectively. The sizes of the mode selection PMOS switch, negative resistance pair and buffer are 3/0.06, 8/0.06 and 16/0.06 μm. The total power consumption of the oscillator core is 12mW. The measured four oscillating frequencies are 42.9, 48.1, 56.4 and 73.7 GHz (Fig 10), and the phase noise at 1MHz offset are -100.3, -95.3, -93.8 and -86.2 dBc/Hz, respectively. Fig. 11 shows the phase noise measurement at 48.1 and 56.4 GHz.

The Figure of Merit (FOM) of a current biased oscillator is given as

$$FOM = \frac{1}{P_{SUPPLY}\,\mathcal{L}\{\Delta\omega\}}\left(\frac{\omega_0}{\Delta\omega}\right)^2 = 2\left(\frac{Q^2}{kT}\right)\left(\frac{A}{\pi F V_{DD}}\right)$$

where $P_{SUPPLY}=V_{DD}I_{BIAS}$ and $A=2 \cdot I_{BIAS}R_P/\pi$. Neglecting the lesser importance of F and assuming that the amplitude is maximized, the FOM is determined by Q. Since in our

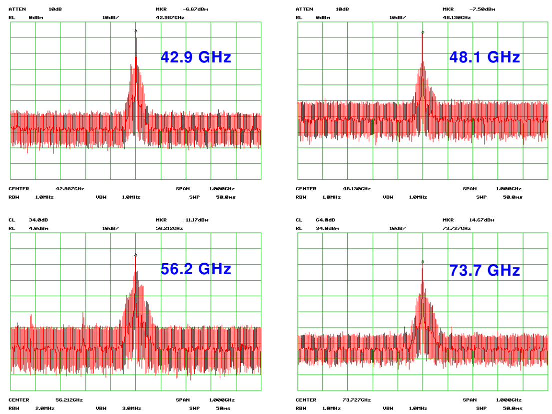


Fig. 10. Measured output spectrums

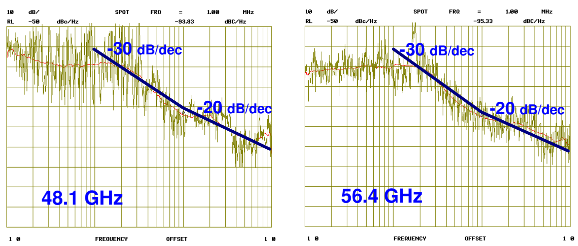
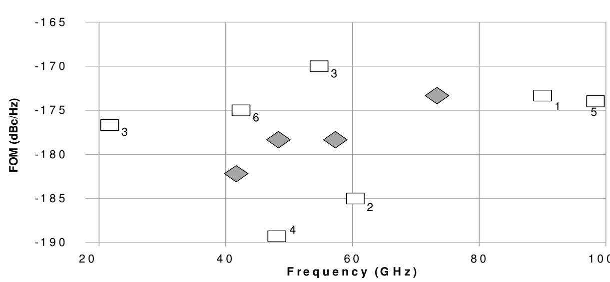


Fig. 11. Measured phase noise

topology the Q is well maintained for all the 4 oscillating frequencies, the proposed quadruple band oscillator has FOM comparable to a state-of-the-art single band oscillator. This is demonstrated in the comparison table and plot in Fig. 12. To ensure a fair comparison, only works with a frequency tuning range less than 5% are included (large continuous tuning typically requires a large varactor, which has a deleterious effect on the Q of mm-wave oscillator.) Fig. 13 shows the chip photograph. The core active area is 200µm×200µm.



Reference	Process CMOS nm	# of band	f_o (GHz)	FTR	P_{DC} (mW)	Phase Noise @1M (dBc/Hz)	FOM (dBc/Hz)
This Work	65	4	42.8	n/a	12	-100.3	-182
			48.1	n/a		-95.3	-178
			56.4	n/a		-93.8	-178
			73.7	n/a		-86.2	-173
1 D. Kim, ISSCC 2009	SOI 32	1	89.9	4.45	7.7	-102.7 @10M	-173
2 L. Li, JSSC 2009	90	1	61.7	4.81	1.2	-90	-185
3 S. Tam, RFIC 2009	90	2	21.3	n/a	14	-100.8	-175.8
			55.3	n/a		-86.7	-170
4 Y. Lin, VLSI 2009	130	1	47.9	1.59	5.6	-102.5	-189
5 C. Cao, JSSC 2006	130	1	98.5	2.5	7	-102 @10M	-174
6 A. van der wel, JSSC 2004	130	1	43	1.7	7	-91	-175

Fig. 12. FOM comparison plot and table.

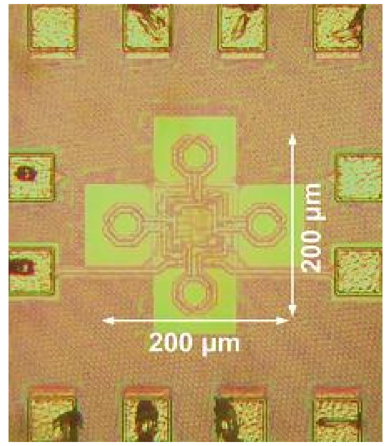


Fig. 13. Die micrograph.

V. CONCLUSION

The developed multiband technique can build an oscillator that can switch between arbitrary 2^N mm-wave bands without degrading Q. The technique breaks the fundamental tradeoff between Q and switching range that exists in classical switched-capacitor and switched-inductor methods. As a result, this even-odd mode 2^N band technique achieves FOMs comparable to single band oscillators.

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