Widely Tunable Inductors Utilizing Transmission-line with Variable Distributed Load Capacitor for Millimeter-wave Applications

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Abstract— This paper proposes a widely tunable inductor realized by transmission lines (T-Line) for applications under 60 GHz. The inductor consists of several L-branch formed by short T-Line segments and variable distributed load capacitors. With changeable load capacitance, the equivalent inductance of whole T-Line would also be tunable. For conceptual demonstration, a prototype T-Line-C VCO is implemented for comparison to the conventional LC VCO. With the same ±50% capacitance variation rate, the traditional LC VCO with lumped inductors for comparison only achieves 11.6% frequency tuning range from 60.5 GHz to 67.6 GHz; However, the demonstrated VCO based on the proposed tunable T-Line inductors improve the frequency tuning range to 25.4% from 53.7 GHz to 68.4 GHz.

1. INTRODUCTION

With the development of high definition (HD) media and the demand of mobilized home entertainment, millimeter-wave (MMW) wireless systems are becoming more and more in demand. Compared to low frequency, MMW frequency bands provides larger bandwidth, faster transfer speed and therefore higher data rate. For example, the IEEE 802.11n wireless standards provides a data rate of 288.8 Mb/s which cost about 12 minutes to transfer a Blu-ray movie of a typical capacity 25 GB. In contrast, the recently approved IEEE 802.11ad standards support a data rate up to 7 Gb/s, which means there would be less than 30 seconds to transfer the same movie. In the meanwhile, in-room media-streaming applications, such as "Air Play", also needs a large date rate which can only be provided by MMW systems. Figure 1 shows 60 GHz bands of different regions.

Figure 1: Unlicensed 60 GHz bands in different regions.

To fully cover 60 GHz bands in different regions, the MMW system is required to have a tuning range at least from 57 GHz to 66 GHz. It poses a great challenge to the MMW integrated-circuits, especially which have large PVT (Process, Voltage and Temperature) variations in modern deep-submicron processes. Unfortunately, design of the key building blocks, e.g., LNA, VCO, and filter, are suffering from lacking tuning elements, which leads to insufficient frequency tuning range for MMW systems. Recently, several VCOs have been developed for MMW applications [1–7]. Some of them focus on the phase noise, however, it has barely any frequency tuning range [1, 4]. Others pay attention to the tuning of varactors and negative resistance MOSFET pair [2, 3], which consumes large power and leads to poor phase noise.

In this paper, a widely tunable inductor realized by transmission-line (T-Line) segments and variable distributed load capacitor is proposed, which provides another dimension for frequency tuning in MMW systems. The T-Line structure performs as an inductor when choosing proper length at the resonant frequency. In our proposed tunable inductor, the T-Line is divided into several short segments. At the connection nodes of each two segments, a variable distributed load capacitor is shunt to ground. By changing the distributed load capacitance, the characteristics of the T-Line would change correspondingly, resulting in the effect of inductance tuning. In modern IC processes, the distributed capacitors in the proposed tunable T-Line inductor can be implemented by the varactors, or even the versus-biased Schottky diodes, which can give larger cutoff frequency and higher Q factor. As a result, it gives us a possibility to realize widely frequency-tunable MMW circuits, such as VCO, LNA, PA and so on.

For conceptual demonstration, a prototype VCO consists of the proposed tunable T-Line inductors is presented. Based on the proposed tunable T-Line based inductor, the VCO is able to improve the frequency tuning range by simultaneously using the tunable inductors and lumped varactors. For comparison, another VCO consisted of lumped inductors is introduced. The simulation results show that the VCO with lumped inductors only has 11.6% frequency tuning range with the lumped tunable varactors, similar to recently published VCOs. In contrast, the demonstrated VCO consists of the proposed tunable inductors achieves a 25.4% frequency tuning range from 53.7 GHz to 68.4 GHz, by simultaneously tuning the variable distributed load capacitance and the lumped varactors. Thus, it is sufficient for MMW applications to cover worldwide 60 GHz bands.

This paper is organized as follows. Section 2 describes the theoretical analysis of the proposed inductor tuning method and architecture of the tunable T-Line inductor. The VCO demonstration for the proposed tunable T-Line inductor and simulation results are shown in Section 3, with comparison of the conventional LC VCO. Finally, conclusion is given in Section 4.

2. PROPOSED T-LINE INDUCTOR

2.1. Variable Distributed Load Capacitor

The equivalent RLGC model for conventional incremental T-Line is shown in Figure 2 excluding the C_L part. R_0 and L_0 are the series resistance and series inductance per unit length, while G_0 and C_0 are shunt conductance and capacitance per unit length, respectively. For an infinite transmission-line, the complex propagation constant and the characteristic impedance are given in (1) and (2). The distributed series inductance and shunt capacitance could be derived in (3) and (4).

$$\gamma = a + j\beta = \sqrt{(R_0 + j\omega L_0)(G_0 + j\omega C_0)} \quad (1)$$
$$Z_0 = \sqrt{(R_0 + j\omega L_0)/(G_0 + j\omega C_0)} \quad (2)$$
$$L_0 = imag(\gamma Z_0)/\omega \quad (3)$$
$$C_0 = imag(\gamma / Z_0)/\omega \quad (4)$$

For a T-Line of length Len, the input impedance of conventional T-Line could be written as (5). In practical applications, the T-Line is one-terminated short for providing DC bias voltage, so that the equivalent input impedance is bridged as (6).

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan(\beta Len)}{Z_0 + jZ_L \tan(\beta Len)} \quad (5)$$
$$Z_{in} = jZ_0 \tan(\beta Len) \quad (6)$$

In the proposed tunable T-Line, a variable distributed capacitor C_L is added into the conventional equivalent RLGC model as Figure 2 shows. Taking $R_0 = G_0 = 0$ to simplify the theoretical

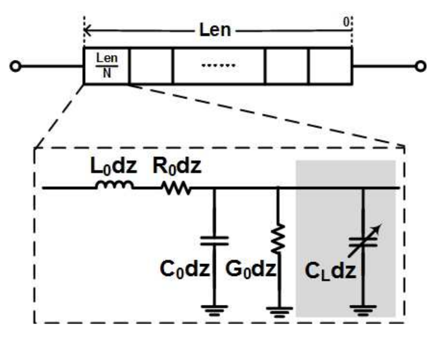


Figure 2: Equivalent RLGC model of the proposed T-Line inductor segment, CLdz is the variable distributed load capacitor.

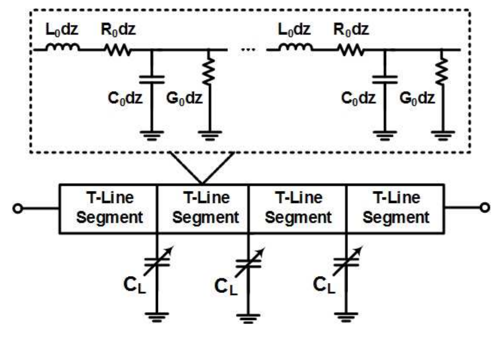


Figure 3: (a) T-Line cell and equivalent circuit; (b) T-Line inductor consisted of T-Line cells; (c) T-Line inductor.

analysis for lossless T-Line, we could get the tunable input impedance as (7).

$$Z_{in,tunalbe} = j\sqrt{\frac{L_0}{C_0 + C_L}} \tan\left[\omega\sqrt{L_0(C_0 + C_L)} \cdot Len\right] \tag{7}$$

The positive imaginary part of the input impedance could be treated as the equivalent inductance of the T-Line. Thus, by tuning the variable distributed capacitor C_L, the equivalent inductance is configurable.

2.2. Practical Tunable T-line Inductor

However, in practical design, it would be impossible for adding real "distributed" load capacitor to T-Line segments of unity length. Then we make an approximation by limiting the segment length of the T-Line. The whole T-Line is divided into N parts, each segment is far smaller than the wavelength. At the connection node of each two segments, a shunt tunable load capacitor is introduced for tuning as Figure 3 shows. Apparently, while N is set larger tending to infinite, the approximation is more close to the real situation. The simulation results show the inductance approximation is quite match while $N \geq 4$. In this case, N is chosen of 4 in demonstration. The variable distributed load capacitor C_L can be realized by MOSFET varactors. It can also be realized by the versus-biased Schottky diodes, which shows much larger cutoff frequency and higher Q factor than conventional varactors.

For demonstration, four T-Line cells are connected serially to form the tunable T-Line inductor. Each T-Line segment is consisted of inductance about 16 pH with distributed load capacitor, which is manufacturable in modern CMOS processes. Figure 4 shows the simulated T-Line inductance with different distributed load capacitance C_L during 50 GHz and 70 GHz. With variable C_L values, the equivalent T-Line inductance shows a large variation range. As shown in Figure 4, the equivalent T-Line inductance changes from 80 pH to 275 pH at 70 GHz while C_L changes from 5 fF to 20 fF.

3. VCO DEMONSTRATION

To prove the effect of the proposed tunable T-Line inductor in MMW applications, we build a prototype VCO based on a standard 65 nm CMOS process. As Figure 5 shows, it consists of the tunable T-Line VCO and the output matching buffer. Figure 6(a) is the conventional LC VCO using fixed inductor for comparison, while Figure 6(b) is the VCO using the proposed tunable T-Line inductors. C_X is the varactor, while C_p is a constant capacitor coming from the parasitic capacitance in real circuits. The C_p is 20 fF which is reasonable assumption with careful layout design. The bias current is 6 mA for both VCOs, chosen as recently state-of-art works did. In the traditional VCO based on the lumped inductor for comparison as shown in Figure 6(a), the lumped inductor L_X is chosen as 80 pH, so that it can be resonant at around 60 GHz with $C_X = 20$ fF.

In the tunable T-Line inductor VCO as shown in Figure 6(b), the tunable T-Line inductor is consisted of 4 serial connected T-Line segments, in which a short T-Line and a load capacitor C_L are included. The tuning of the distributed capacitor C_L can be realized by varactors or versus-biased Schottky diodes in modern IC processes. As we mentioned before, we choose the segment

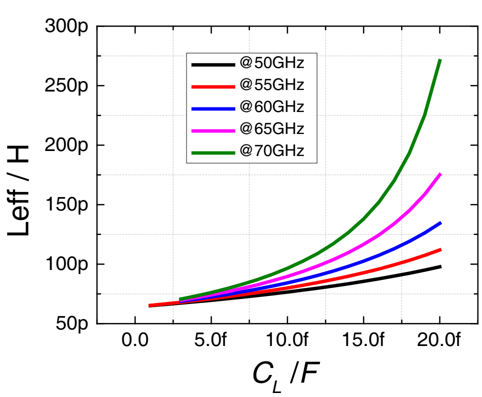


Figure 4: Simulation equivalent inductance of the tunable T-Line inductor with variable distributed capacitance C_L.

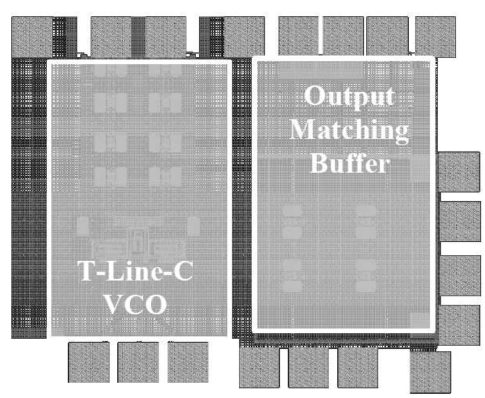
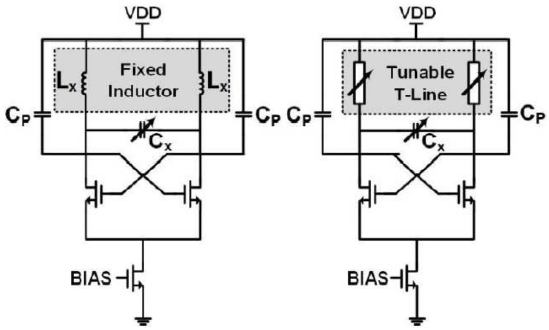


Figure 5: The Layout of the proposed T-Line-VCO and the output matching buffer.



(a) (b)

Figure 6: (a) Schematic of the LC VCO consists of fixed inductor L_X and varactor C_X; (b) Schematic of the VCO consists of tunable T-Line inductor and varactor C_X.

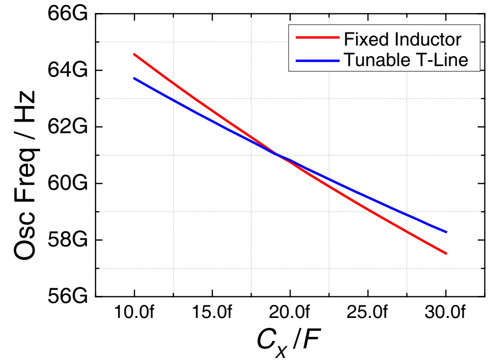


Figure 7: The frequency tuning range of both fixed L_X and tunable T-Line with changeable varactor C_X.

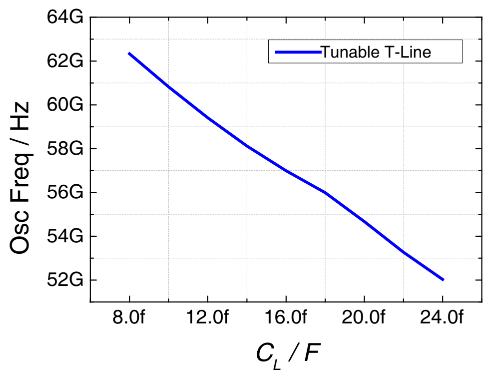


Figure 8: Oscillator frequency tuning range of tunable T-Line inductor VCO with variable load capacitance C_L (8 fF to 24 fF, 2 fF per step).

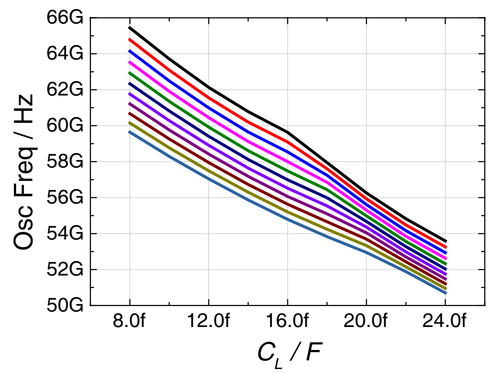


Figure 9: Oscillator frequency with both varactor C_X (10 fF to 30 fF, 2 fF per step) and distributed load capacitance C_L (8 fF to 24 fF, 2 fF per step).

Table 1: Comparison of recent state-of-art works.

	[1] JSSC 2009	**[2] RFIC 2009**	**[3] MWCL 2010**	**[4] ISCAS 2010**	**[5] JSSC 2011**	**[6] MTT 2011**	**This work**
Technology	90 nm CMOS	65 nm CMOS	0.18 µm CMOS	65 nm CMOS	65 nm CMOS	65 nm CMOS	0.18 µm CMOS
VDD (V)	0.43	1.2	2.5	1.5	1	1	1.8
Center Frequency (Hz)	60 G	56 G	69 G	77 G	58.2 G	-	
Frequency Range (Hz)	58.8 G–61.7 G	-	64.2 G–69.4 G	72.8 G–77.6 G	56 G–60.4 G	81 G–86 G	50.7 G ∼ 65.44 G
Tuning Range	4.81%	17%	7.6%	6.27%	7.6%	-	25.4%
Output Power (dBm)	−19	−9.8	−18.5	-	-	-	-
Phase Noise (dBc/Hz)	−90@1 MHz	−99.4@1 MHz	−76@1 MHz	−109@10 MHz	−95/ − 97 @1 MHz	−84@1 MHz	-
Power (W)	1.2 m	15 m	27.5 m	15.81 m	22 m	65 m	5 m∼17.5 m

inductance of 8 pH, $C_L = 10$ fF to let the VCO also oscillate at about 60 GHz with $C_X = 20$ fF. The distributed load capacitor C_L can be changed to realize the tunable inductor to further enhance the frequency tuning range.

We fix the distributed load capacitor C_L of 10 fF in the tunable T-Line, then the two oscillate frequencies change from 60.5 GHz to 67.6 GHz and from 61.3 GHz to 66.7 GHz with varactor C_X from 10 fF to 30 fF, respectively as Figure 7 shows.

The VCO based on the tunable T-Line inductor is also able to realize frequency tuning by changing the distributed load capacitor C_L. Figure 8 shows the oscillator frequency tuning curves of the tunable T-Line inductor VCO with variable distributed capacitor C_L. As C_L changes from 8 fF to 24 fF, the oscillator frequency changes from 55.0 GHz to 65.3 GHz. Take frequency at $C_L = 16$ fF as the center frequency, the tuning range is about 18.1% with ±50% C_L variation.

In addition, the VCO based on the tunable T-Line inductor can further enhance the frequency tuning range by changing the distributed load capacitor C_0 and the lumped varactors C_L simultaneously. In Figure 9, the C_X varies from 10 fF to 30 fF, 2 fF as a step, and the C_L varies from 8 fF to 24 fF, 2 fF as a step. Take 58 GHz as the center frequency, the frequency tuning range is around 25.4% from 53.7 GHz to 68.4 GHz. The whole tuning range could cover worldwide 60 GHz bands, which is appropriate for MMW applications. Table 1 gives the comparison among recent state-of-art works.

4. CONCLUSION

In this paper, a widely tunable T-line inductor realized by variable distributed load capacitor is proposed. As the theoretical analysis, the T-Line could be realized as a tunable inductor by changing the distributed load capacitance of each short segment of the T-Line. For conceptual demonstration, a prototype VCO are demonstrated, consisted of tunable T-Line inductor and distributed load capacitors. With ±50% capacitance variation rate, the conventional VCO based on the fixed inductors for comparison only has 11.6% frequency tuning range, while the demonstrated VCO with the proposed tunable T-Line inductors has 25.4% tuning range from 53.7 GHz to 68.4 GHz with both varactors and distributed load capacitor tuning. It gives us another dimension to improve the frequency tuning range for MMW VCO. Furthermore, it also gives us a potential to achieve large frequency tuning range for other MMW modules, such as LNA, PA, which utilize T-Lines as the passive network.

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