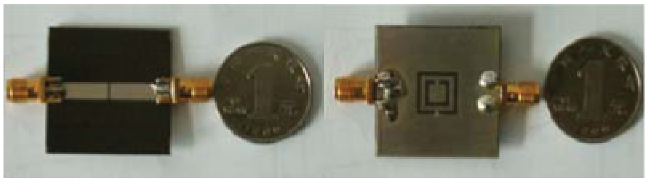

Figure 5 Photographs of the fabricated SRR DGS CRLH TL unit. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

In the equation $n = c\sqrt{\mu\varepsilon}$, μ and ε may be positive or negative. Suppose $\omega_S < \omega_{se} < \omega_{sh}$, then the values of μ and ε can be derived from (8) and (9), respectively. As for the proposed SRR DGS CRLH TL, the refraction index changes remarkably as shown in Figure 4(c). If $f_S < f < f_{se}$, $n < 0$,, which shows left-handed property. If $f_{sh} < f < \infty$, then $0 < n < c\sqrt{L_R C_R}$, which shows right-handed property.

4. MEASUREMENT RESULT

To verify the left-handed property of this structure, the SRR DGS CRLH TL unit model is fabricated as illustrated in Figure 5, which is composed of teflon substrate with thickness $h = 1$ mm and dielectric constant $\varepsilon_r = 2.65$, the conductor line has a width of 4 mm, the strip-gap c has a little difference from the earlier analysis, so the transmission zero moves to $f_S = 1.3$ GHz. The measured magnitude of S_{21} shows a good agreement with the simulation results by EM simulator Ansoft HFSS software v9, but the phase has a small shift (Fig. 6). This structure has a transmission zero and takes on left-handed highpass property at low frequency range and right-handed lowpass property at high frequency range.

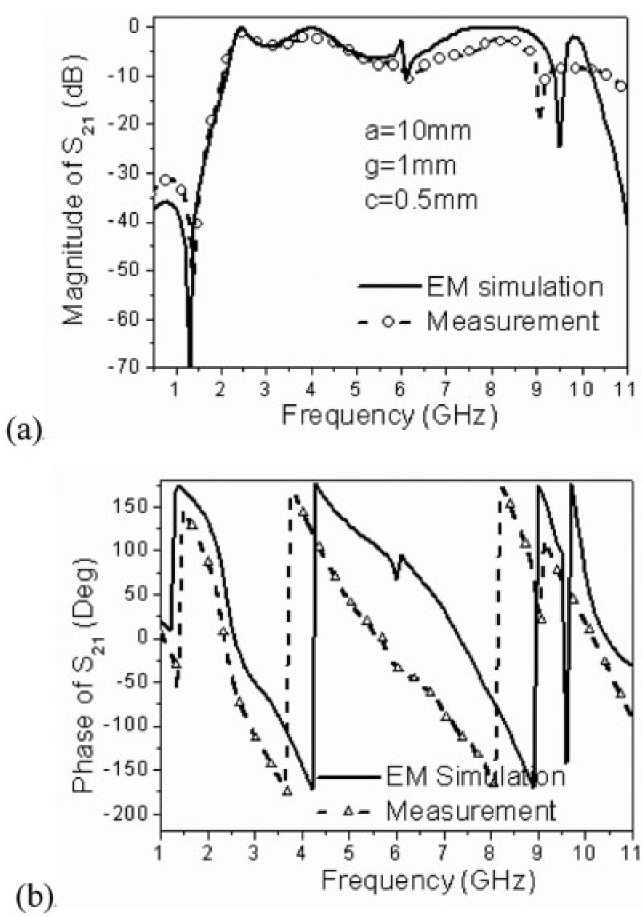

Figure 6 Comparison between EM simulation result and measurement result. (a) Magnitude of S_{21}, (b) Phase of S_{21}

5. CONCLUSION

A split-ring resonator defected ground structure CRLH TL unit model is investigated, which has the advantages of having transmission zero and no grounded via. The dispersion relation, impedance property as well as refraction index are derived to take on left-handed property between the transmission zero location and the transmission forbidden gap. Other kinds of SRR DGS CRLH TL can be achieved by replacing the series gap by interdigital capacitor or lumped capacitor, which can be applied to microwave integrated circuit design.

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REFERENCES

1. V.G. Veselago, The electrodynamics of substances with simultaneously negative values of ε and μ, Sov Phys Usp 10 (1968), 504–514.
2. C. Caloz and T. Itoh, Application of the transmission line theory of left-handed (LH) materials to the realization of a microstrip 'LH line,' APS IEEE 2 (2002), 16–21.
3. C. Caloz and T. Itoh, Transmission line approach of left-handed (LH) materials and microstrip implementation of an artificial LH transmission line, IEEE Trans Antennas Propag 5 (2004), 1159–1166.
4. A. Grbic and G.V. Eleftheriades, Experiment verification of backward wave radiation from a negative refractive index metamaterial, J Appl Phys 92 (2002), 5930–5935.
5. G.V. Eleftheriades, A.K. Iyer, and P.C. Kremer, Planar negative refractive index media using periodically L–C loaded transmission lines, IEEE Trans Microwave Theory Tech 12 (2002), 2297–2305.
6. C.S. Kim, J.I. Park, A. Dal, et al., A novel 1-D periodic defected ground structure for planar circuits. IEEE Microwave Guided Wave Lett 4 (2000), 131–133.
7. J. Bonache, F. Martin, et al., Application of complementary split-ring resonators to the design of compact narrow band-pass structures in microstrip technology, Microwave Opt Technol Lett, 46 (2005), 508–512.
8. J.D. Baena, J. Bonache, F. Martin, et al., Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines, IEEE Trans Microwave Theory Tech 4 (2005), 1451–1460.

INJECTION-LOCKED GaInP/GaAs HBT FREQUENCY DIVIDER WITH STACKED TRANSFORMERS

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ABSTRACT: *The first integrated GaInP/GaAs heterojunction bipolar transistor (HBT) injection-locked frequency divider (ILFD) with the stacked transformers is demonstrated around 10 GHz. The stacked*

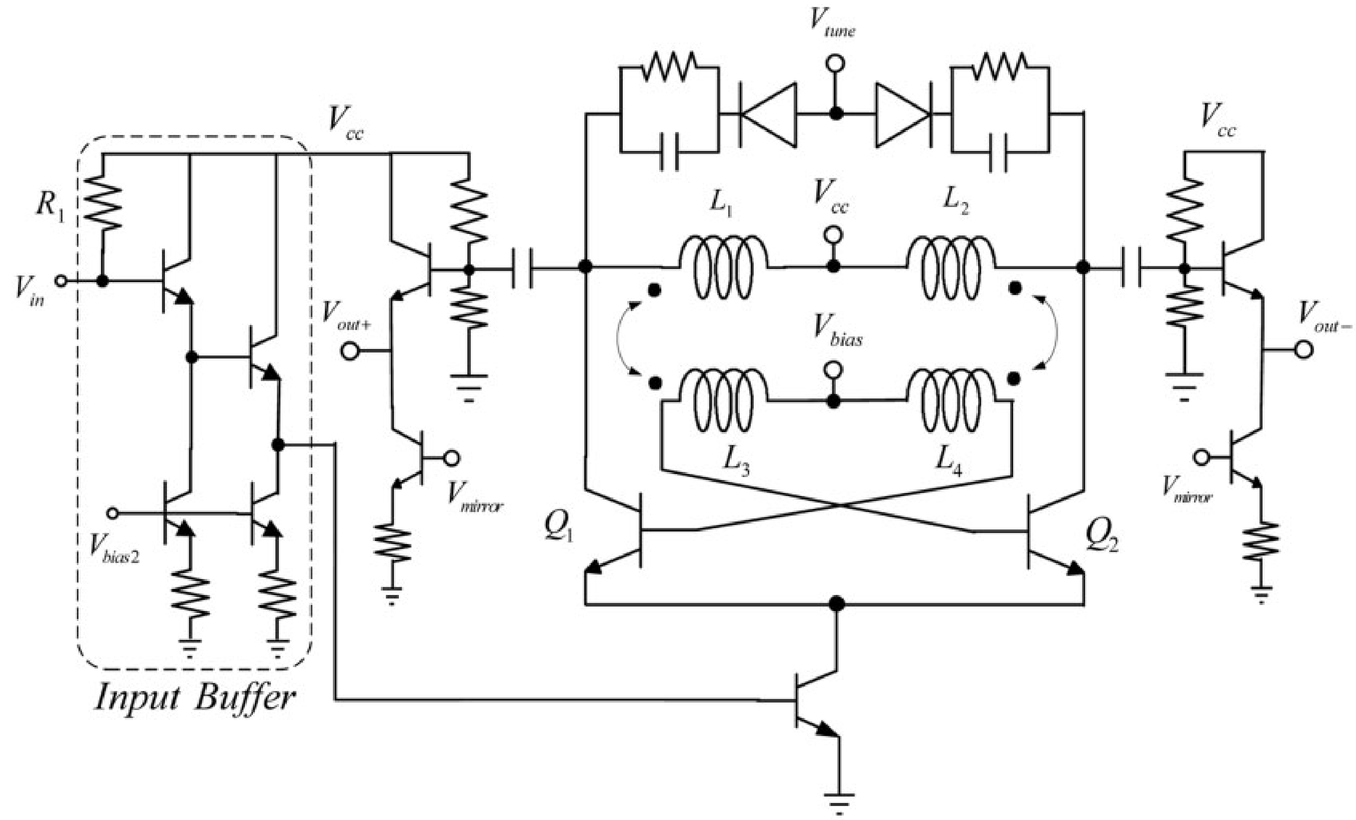

Figure 1 Schematic of the GaInP/GaAs HBT injection-locked frequency divider

transformers formed by only two metal layers provide the inductive coupling in the cross feedback and separate biasing for base and collector to allow for the larger output swing in the LC tank and obtaining wide locking range. Under the supply voltage of 5 V and core power consumption of 20.5 mW, the locking range is 7.8% of the center operating frequency. The chip size of the entire ILFD including probing pads is 1.0 × 1.0 mm². Microwave Opt Technol Lett 49: 2602–2605, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22737

Key words: *injection-locked frequency divider (ILFD); stacked transformer; GaInP/GaAs; heterojunction bipolar transistor*

1. INTRODUCTION

With the increasing demands on the communication services, higher data-rate and accurate channel-selection are required. In the most of applications, frequency synthesizers play important roles in the frequency translation. The main concern for them is to design a high-frequency and low-power frequency divider. Digital flip-flop-based frequency dividers, such as static [1] and high speed latching operation flip-flop (HLO-FF) [2] structures, have the property of wide-band, but their maximum operating frequencies are limited by the gate-delay of the emitter-coupled logic pair. Furthermore, the complicated digital stages also increase the power consumption.

Another type of divider belongs to the analog structure, such as the regenerative frequency divider (RFD) [3] and the injection-

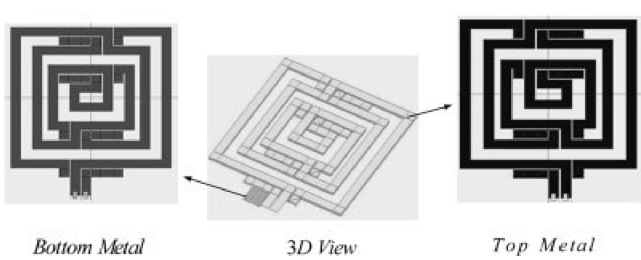

Figure 2 Schematic of the stacked transformer

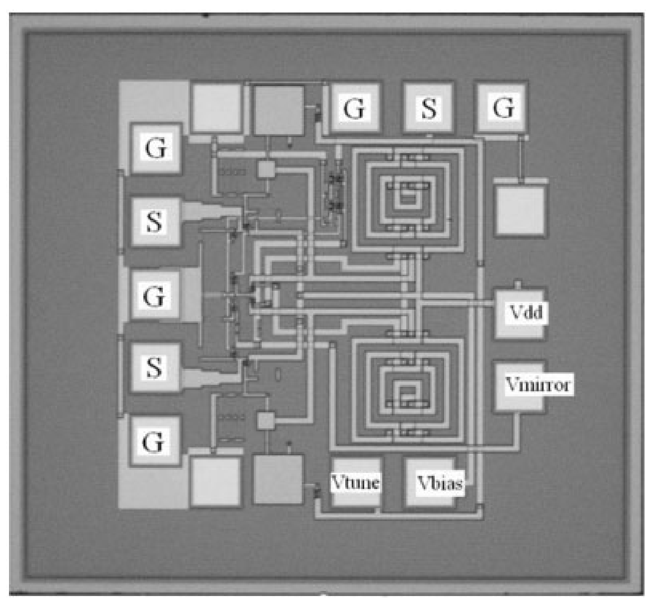

Figure 3 Die photo of the GaInP/GaAs HBT injection-locked frequency divider (1.0 × 1.0 mm²)

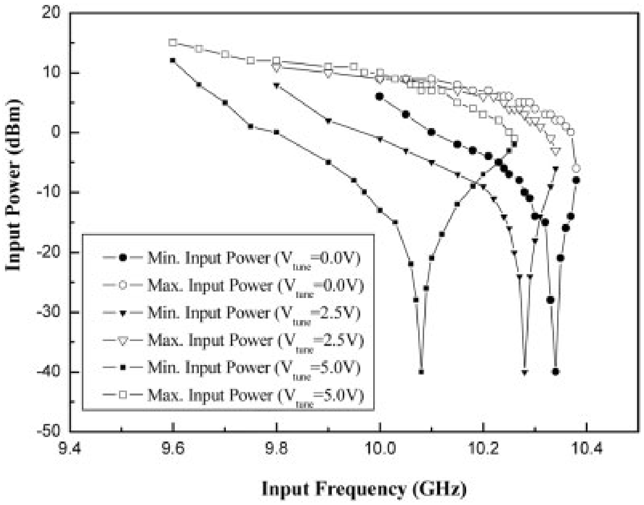

Figure 4 The input sensitivity of the GaInP/GaAs HBT injection-locked frequency divider

locked frequency divider (ILFD) [4–6]. Although analog frequency dividers have the limitation in the minimum operating frequency, the properties of low power consumption makes RFD and ILFD more attractive for higher frequency or narrow-band personal wireless application. RFD can operate at higher frequency than digital dividers can. However, they have the limited fractional bandwidth and only divide-by-two ratio. Because RFD consists of a mixer, a low-pass filter, and an amplifier, the RFD is still not the best candidate for low-power applications.

When compared with the aforementioned dividers, ILFD consumes lowest power and provides division ratio more than two. Most of the ILFDs are based on the VCO structures [7–9], which are the emitter-coupled pair with cross feedback. In the conventional direct coupling structure, the voltage swing of the LC resonator is restricted by the base-collector diode of transistor [7]. In this work, the stacked transformers as the inductive coupling are used to enlarge the output swing and obtain the wider locking range. In addition, the GaInP/GaAs heterojunction bipolar transistor (HBT) technology has inherent properties for the high-frequency design, such as low base resistance, suppression of trap-related 1/f noise, and semi-insulating GaAs substrate.

2. CIRCUIT DESIGN

Figure 1 shows the schematic diagram of the transformer-based ILFD using a tail current source as a signal injector. It consists of a conventional cross-coupled differential emitter pair for compensating the loss in the LC tank, two staked transformers as inductive coupling, and two diode-connected transistors (base-emitter junctions) as varactors. For the transformer inductive coupling, the base is no longer tied with the collector directly. The collector can be biased at a higher voltage to enlarge the output voltage swing.

The vertical stacked transformers proposed by Zannoth et al. [7] are laid out as symmetrical quadratic spirals. In the GaInP/GaAs HBT process, only two metal layers (thickness of 1.6 and 1.0 μm) can be used for the stacked structure. The primary coil (L_1 and L_2) connected to the collectors and the secondary coil (L_3 and L_4) connected to the bases have the inductance of 3.14 and 2.57 nH, respectively. L_1–L_4 are mutually coupled with a magnetic coupling factor of 0.8. The primary coil formed by the thicker metal is to minimize the loss of the stacked transformer LC tank. The top and 3D viewpoints are displayed in Figure 2. On the other hand, the transformer between the supply voltage and the transistors, Q_1 and Q_2, provide the RF chock to avoid signal leakage. For biasing the diode-connected transistors, resistors are connected in parallel to the capacitors. At the high frequency, these resistors can be neglected because their impedance is higher than that of capacitors. The input cascade emitter followers with on-chip 50-Ω shunting resistors (R_1) provide wideband matching. At the same

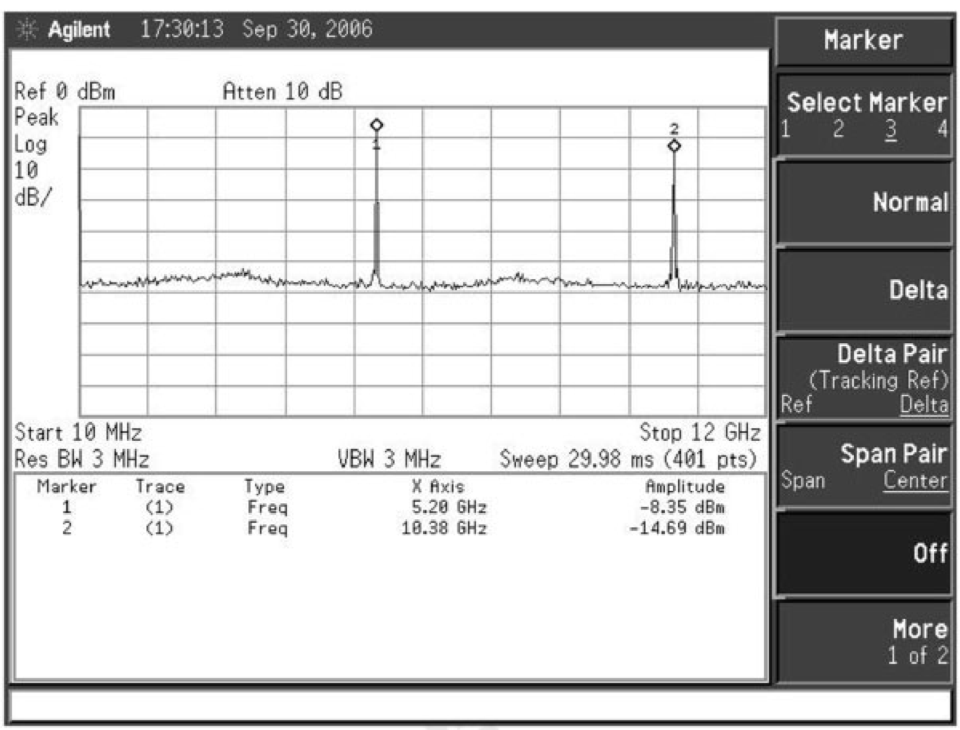

Figure 5 The output spectrum of GaInP/GaAs HBT injection-locked frequency divider with the maximum input frequency signal (10.38 GHz)

time, the output common collector buffer generates the low impedance for 50-Ω measurement system.

3. EXPERIMENTAL RESULTS

The ILFD has been designed and fabricated in 2 μm GaInP/GaAs HBT technology. The die photo is displayed in Figure 3 and its size is 1.0 × 1.0 mm^2.

The devices used in the circuit have a peak f_{MAX} of 50 GHz and peak f_T of 40 GHz. HBT devices of 2 × 6 μm^2 and 2 × 4 μm^2 are used for cross-coupled core and input buffer, respectively. For the larger tuning range, the sizes of varactors are increased to 3 × 12 μm^2. The chip was on-wafer measured using 50-Ω GSG RF probes, GSGSG RF probes, and DC probes.

The core circuit of ILFD consumes a supply current of 4.1 mA at the supply voltage of 5 V. Input sensitivity versus frequency is presented in Figure 4. The different tuning voltages of 0, 2.5, and 5 V separately have the locking range of 380, 540, and 660 MHz. The total locking range is from 9.60 to 10.38 GHz and about 7.8% of the operating center frequency. Figure 5 shows the output spectrum of ILFD with the maximum input frequency of 10.38 GHz. The locking range as a function of incident power is depicted in Figure 6. The locking range is limited by phase condition at low input power, and increases with incident input power until ILFD enters the gain-limited condition. It reaches the maximum peak at the input power of 1–2 dBm. Then, the gain-limited condition shrinks the locking range. The maximum locking ranges of 510, 400, and 290 MHz are separately at the tuning voltage of 5.0, 2.5, and 0 V. The phase noise of the free-running, injection-locked, and reference signals is measured by an Agilent E5052A signal source analyzer, as shown in Figure 7. In the (locking) in-band range, the locked signal tracks the low-phase-noise reference signal and provides the obvious improvement of phase noise (about 39 dB at 100-kHz offset frequency) over free-running signal.

4. DISCUSSION AND CONCLUSIONS

This work describes the design and performance of ILFD with stacked transformers fabricated in the 2 μm GaInP/GaAs HBT technology. The stacked transformers formed by only two metal layers provide the inductive coupling in the cross feedback. The independent biasing between base and collector allows the larger voltage swing in the LC tank and obtains the wide locking range. The locking range of 9.6–10.38 GHz is 7.8% of the center operating frequency. The core circuit of ILFD consumes a supply current of 4.1 mA at the supply voltage of 5 V.

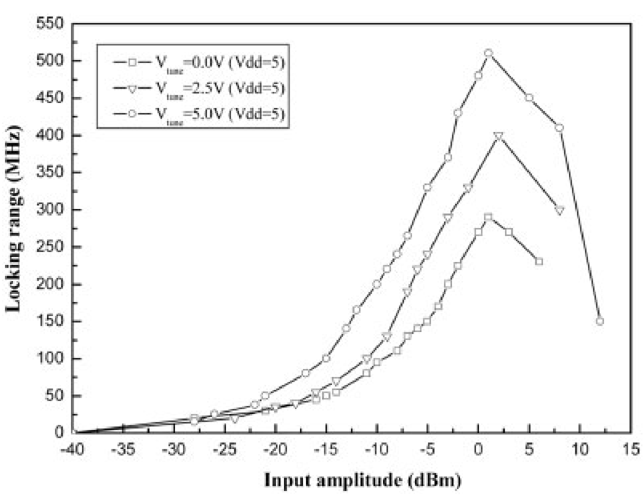

Figure 6 Locking range as a function of incident power in the ILFD

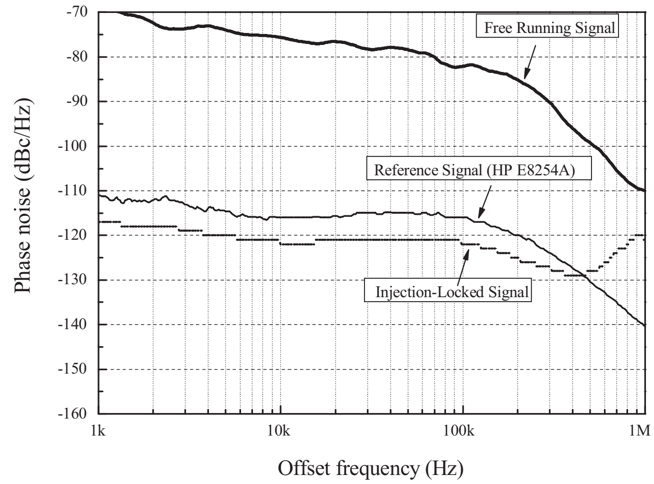

Figure 7 Measured phase noise of the reference, injection-locked, and free-running signals

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REFERENCES

1. M. Mohktahri, C.H. Fields, R.D. Rajavel, M. Sokolich, J.F. Jensen, and W.E. Stanchina, 100+ GHz static divide-by-2 circuit in InP-DHBT technology, IEEE J Solid-State Circuits 38 (2003), 1540-1544.
2. K. Murata, T. Otsuji, E. Sano, M. Ohhata, M. Togashi, and M. Suzuki, A novel high-speed latching operation flip-flop (HLO-FF) circuit and its application to a 19-Gb/s decision circuit using a 0.2-μm GaAs MESFET, IEEE J Solid-State Circuits 30 (1995), 1101-1108.
3. H. Ichhino, N. Ishihara, M. Susuki, and S. Konaka, 18-GHz 1/8 dynamic frequency divider using Si bipolar technology, IEEE J Solid-State Circuits 24 (1989), 1723-1728.
4. R. Adler, A study of locking phenomena in oscillators, Proc IRE 34 (1946), 351-357.
5. H.R. Rategh and T.H. Lee, Superharmonic injection-locked frequency dividers, IEEE J Solid-State Circuits JSSC-34 (1999), 813-821.
6. A. Mazzanti, P. Uggetti, and F. Svelto, Analysis and design of injection-locked LC dividers for quadrature generation, IEEE J Solid-State Circuits 39 (2004), 1425-1433.
7. M. Zannoth, B. Kolb, J. Fenk, and R. Weigel, A fully intergrated VCO at 2 GHz, IEEE J Solid-State Circuits 33 (1998), 1987-1991.
8. S.A. Yu, C.C. Meng, and S.S. Lu, A 5.7 GHz interpolative VCO using InGaP/GaAs HBT technology, IEEE Microwave Wireless Compon Lett 12 (2002), 37–38.
9. T. Wang, H.-C. Chen, H.-W. Chiu, Y.-S. Lin, G.W. Huang, and S.-S. Lu, Micromachined CMOS LNA and VCO by CMOS compatible ICP deep trench technology, IEEE Trans Microwave Theory Tech 54 (2006).