Low phase noise oscillator based on quarter mode substrate integrated waveguide technique

Ziqiang Yang\textsuperscript{1a), Bangyu Luo\textsuperscript{1, Jun Dong\textsuperscript{1, Tao Yang\textsuperscript{1, and Haiyan Jin\textsuperscript{2}}}

\textsuperscript{1} School of Electronic Engineering, University of Electronic Science and Technology of China, No. 2006, Xiyuan Ave, West Hi-Tech Zone, Chengdu, 611731, China
\textsuperscript{2} School of Communication and Information Engineering, University of Electronic Science and Technology of China, No. 4, Section 2, North Jianshe Road, Chengdu, 610054, China
\textsuperscript{a)} yangziqiang@uestc.edu.cn

Abstract: A low phase noise oscillator based on the quarter mode substrate integrated waveguide (QMSIW) technique is presented for the first time. The proposed oscillator is stabilized with the TE\textsubscript{101} mode of a QMSIW resonator, which is 25\% the size of the substrate integrated waveguide (SIW) resonator. In order to obtain a high loaded quality factor, the coupling coefficient between the QMSIW cavity and microstrip is tuned to be undercoupled. A X-band Prototype has been designed and fabricated. By using the QMSIW resonator, the fabricated oscillator has a more compact size than the SIW counterpart. The measured results show that the oscillator has a phase noise of $-98.5$ dBc/Hz at 100 kHz at 9.03 GHz, and an output power of 5.04 dBm with a DC consumption of 20 mW.

Keywords: quarter mode substrate integrated waveguide (QMSIW), oscillator, phase noise, resonator

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Nowadays, low-phase noise, low-cost oscillators are more and more useful in microwave circuits and modules for modern communication systems to provide high spectral pure signal sources. In order to reduce the phase noise, the frequency stabilizing resonators, such as microstrip resonators, conventional cavity resonators and substrate integrated waveguide (SIW) resonators, are introduced in the oscillator circuits. The microstrip resonators are widely used in the planar oscillator circuits, because they are compact and easy to be realized by the standard PCB process. But the poor quality (Q) factor of the microstrip resonators restricts the phase noise performance of the oscillators. The conventional cavity resonators, such as dielectric and metal waveguide cavity resonators, possess high Q factor. Nevertheless, their bulky size and 3D structure make them difficult to be integrated in the planar circuits. In recent years, the SIW has been studied and exploited to design the high performance planar resonators, for its low cost, low insertion loss, high Q factor, and compatible with the planar PCB process. Based on the SIW resonators, several low phase noise oscillators have been developed [1, 2, 3, 4]. However, these SIW resonators are relatively large compared with the microstrip resonators.

Recently, the half mode substrate integrated waveguide (HMSIW) and quarter mode substrate integrated waveguide (QMSIW) have been proposed to reduce the sizes of the SIW devices [5]. It was demonstrated in [6] that the HMSIW can be obtained by bisecting the SIW with a fictitious magnetic wall, and the new structure can preserve the field distribution of the original SIW. The HMSIW can be further bisected with another fictitious magnetic wall and the each half of the HMSIW becomes a QMSIW structure [7]. Hence, the QMSIW has only 25% size of the SIW, and the advantages of the SIW are preserved. So the QMSIW resonators can be used to develop a novel low phase noise oscillator.

In this paper, an oscillator based on the QMSIW resonator is designed, fabricated and measured. The oscillator has a more compact size in contrast to the SIW counterpart. The measured results show that the phase noise is $-98.5 \text{ dBc/Hz}$ at 100 kHz offset from the 9.03 GHz oscillation frequency and the figure-of-merit (FOM) is $-184.6 \text{ dBc/Hz}$. The power consumption is 20 mW from a 2.0 V supply voltage.

2 Design and analysis of the QMSIW resonator

The SIW structure acts closely to a conventional rectangular waveguide. And the resonant frequency of the dominant $\text{TE}_{101}$ mode is calculated as the following formula [8]:

\[ f = \frac{c}{2L} \left( \frac{1}{\sqrt{2}} \right) \sqrt{n_1^2 - n_2^2} \]

where $f$ is the resonant frequency, $L$ is the length of the SIW, $c$ is the speed of light, $n_1$ is the refractive index of the dielectric, and $n_2$ is the refractive index of the substrate.
\[ f_{\text{TE}_{\text{eff}}} = \frac{c}{2\sqrt{\mu_r \varepsilon_r}} \sqrt{\left( \frac{1}{W_{\text{eff}}} \right)^2 + \left( \frac{1}{L_{\text{eff}}} \right)^2} \]  

(1)

Where \( c \) is the velocity of light in vacuum, \( \varepsilon_r \) and \( \mu_r \) are the permittivity and permeability of the substrate material. In addition, \( W_{\text{eff}} \) and \( L_{\text{eff}} \) are given by:

\[ W_{\text{eff}} = W_{\text{SIW}} - \frac{D^2}{0.95S}, \quad L_{\text{eff}} = L_{\text{SIW}} - \frac{D^2}{0.95S} \]  

(2)

Where \( W_{\text{SIW}} \) and \( L_{\text{SIW}} \) are the width and length of the SIW cavity, \( D \) and \( S \) are the diameter of vias and the distance between two neighboring vias.

\[ \frac{1 - \beta}{1 + \beta} \]  

(3)

Where \( R_L \) is the return loss of the input port and \( \beta \) is the coupling coefficient at the resonant frequency. From the equation above, an under-coupling case (\( \beta < 1 \)) and over-coupling case (\( \beta > 1 \)) are corresponding to an \( R_L \), respectively.

In order to reduce the phase noise of the oscillator, the QMSIW resonator should provide a high loaded \( Q_L \)-factor. The relationship among the coupling coefficient, loaded \( Q_L \)-factor and unloaded \( Q_U \)-factor can be described as [9]:

\[ Q_L = \frac{Q_U}{1 + \beta} \]  

(4)

According to (4), the under-coupling case (\( \beta < 1 \)) contributes to a higher \( Q_L \). Hence, the insertion depth of the coupling microstrip (\( L_g \)) and the width of the
coupling slot (G) in Fig. 1(a) are tuned to get an under-coupling case in this design. The proposed QMSIW resonator is simulated and optimized using a finite element method (FEM) based on the 3D electromagnetic simulator (Ansoft HFSS). The final dimensions of the geometrical parameters chosen for the design of the QMSIW resonator are $W_p = 0.6$ mm, $G = 0.3$ mm, $L_g = 1.2$ mm, $T = 1.12$ mm, $D = 0.64$ mm, $S = 1.14$ mm, $W = 7.76$ mm and $L = 7.66$ mm. The simulated results are given in Fig. 1(b).

3 Design and implementation of the oscillator

The physical configuration of the oscillator based on the QMSIW resonator is shown in Fig. 2. An InGaAs HEMT MGF4941AL from Mitsubishi is selected as the active device. The bias networks are carefully designed and applied to the gate and drain of the transistor. Each of the bias networks consists of a $\lambda/4$ microstrip line and a radial stub. The source side of the HEMT is connected by a short stub with a length $L_s$ to generate a positive feedback. The $L_s$ is optimized for maximum negative resistance. The QMSIW cavity coupled with a 100 $\Omega$ microstrip line is employed at the gate side and the length of the microstrip line is tuned to meet the oscillation conditions:

$$|\Gamma_r| > 1/|\Gamma_{in}|$$
$$\text{Arg}(\Gamma_r) = \text{Arg}(1/\Gamma_{in})$$

The output matching circuit is designed to transfer the maximum power to the load. A coupling filter is used at the output side to restrain the harmonics. The Advanced Design System 2009 (ADS 2009) software is used to optimize all the network elements mentioned above.

4 Experimental results

The fabricated oscillator, which is shown in Fig. 3, is measured at a bias voltage of $V_{DS} = 2$ V and a drain current of $I_D = 10$ mA. Fig. 4 shows the measured output spectrum of the oscillator with Agilent PXA Signal Analyzer N9030A. The measured output power is 5.04 dBm at oscillation frequency of 9.03 GHz (the loss...
of the cable used in the measurement is about 2 dB). Furthermore, Rohde and Schwarz signal source analyzer FSUP50 is utilized to accurately measure the phase noise performance. Fig. 5 shows the simulated and measured phase noise at different offsets from the carrier. The measured phase noises at 100 kHz and 1 MHz offset from the oscillation frequency are $-98.5 \text{ dBc/Hz}$ and $-119.2 \text{ dBc/Hz}$, respectively.

![Photograph of the fabricated oscillator.](image)

**Fig. 3.** Photograph of the fabricated oscillator.

![Output spectrum with span of 2 MHz for the oscillator.](image)

**Fig. 4.** Output spectrum with span of 2 MHz for the oscillator

![Simulated and measured phase noise of the oscillator](image)

**Fig. 5.** Simulated and measured phase noise of the oscillator
Table I shows a comparison of the oscillators based on the hybrid integrated circuit technology. The FOM is an important parameter to evaluate the performance of the oscillators at different frequencies, which is defined as \[ \text{FOM} = -20 \log \left( \frac{f_0}{\Delta f} \right) + L(\Delta f) + 10 \log \left( \frac{P_{DC}}{1 \text{ mW}} \right) \] (7)

Where \( f_0 \) is the oscillation frequency, \( \Delta f \) is the frequency offset from the \( f_0 \), \( L(\Delta f) \) is the phase noise and \( P_{DC} \) is the total DC power consumption in mW.

| Ref. | Device | Resonator         | \( f_0 \) GHz | L (100 kHz) dBc/Hz | FOM dBc/Hz |
|------|--------|-------------------|---------------|--------------------|------------|
| [1]  | pHEMT  | SIW resonator     | 9.5           | -92                | -184      |
| [4]  | HEMT   | SIW resonator     | 11.48         | -100.3             | -186.8    |
| [4]  | HEMT   | Microstrip resonator | 11.87     | -92.1             | -178.6    |
| This work | HEMT | QMSIW resonator | 9.03         | -98.5             | -184.6    |

5 Conclusion

A low phase noise oscillator based on the QMSIW technique is presented for the first time. The oscillator is designed based on the negative resistance concept. The experimental results show that the phase noise of the proposed oscillator is much lower than that of the microstrip resonator oscillator and is comparable with that of the SIW counterpart. Meanwhile, the QMSIW oscillator has a more compact size than the SIW oscillator, which makes it suitable for lower frequency band (less than few GHz) applications.

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