Varactor-Tuned Dual-Mode Frequency Discriminator for Instantaneous Frequency Measurements

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***Abstract*—In this paper a novel varactor-tuned frequency discriminator that makes use of two tunable dual-mode microstrip resonators is demonstrated which doubles the discriminator tuning bandwidth. To prove its validity a prototype of the tunable dual-mode microstrip resonator is manufactured and the measured results are used to study the frequency discriminator response. This new approach can cover almost an octave of frequency range from 1.05 to 2 GHz with a sensitivity of 45 V/GHz and 21 V/GHz for the first and second mode, respectively.**

***Keywords*—Instantaneous frequency measurement (IFM), frequency discriminator, dual-mode resonator, microstrip resonator, tunable resonator.**

I. INTRODUCTION

Frequency discriminators are important microwave subsystems used in many applications such as: i) electronic intelligence systems and radar warning for the determination of unknown signals [1], ii) characterization and measurement of the phase noise in local oscillator [2], and iii) phase noise reduction of Voltage Controlled Oscillators (VCO) working inside a Frequency Locked Loop (FLL) [3].

Although there are some architectures that can perform fast instantaneous frequency measurements, the delay-line frequency discriminator [4] has attracted a considerable attention in the recent years [1,2,5,6]. This type of discriminator makes use of a delay line to compare the phase of the input signal and measure its frequency. The main limitation of this circuit is the long external delay line required to get a proper frequency sensitivity. This increases the size of the circuit, and precludes its integration in planar technologies.

An interesting alternative to reduce the size and the complexity of the former approach is the balanced double-tuned frequency discriminator [7]. This circuit makes use of the slope property of two non-interacting resonant circuits around the center frequency to get an output signal that has a linear dependency with the instantaneous frequency of the input signal. The main drawbacks of this approach in planar technologies is its limited bandwidth and sensitivity due to the relatively low tuning range and quality factor of the tuning elements [5,8].

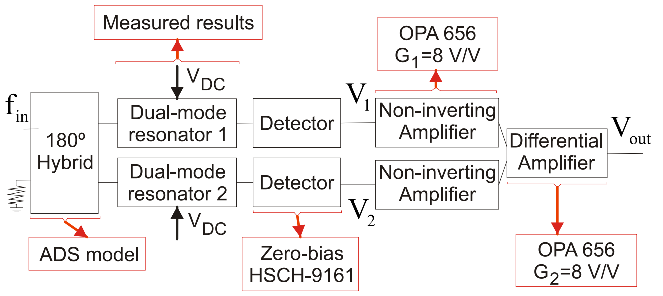


Fig. 1. Block diagram of the varactor-tuned dual-mode frequency discriminator. The red boxes give information about each element used in the final simulation performed in section IV.

To solve these limitations, in this paper we propose a novel varactor-tuned frequency discriminator that makes use of two tunable dual-mode microstrip resonators to increase its potential frequency range. Dual-mode resonators have attracted considerable attention in the recent years [8,9] and are used as doubly tuned resonant circuits to halve the number of resonators required in filter's design. However, in our proposal the two tuned modes of these resonators are used independently to cover different frequency ranges, potentially doubling the tuning frequency range, and making the design of compact broadband frequency discriminators feasible.

To prove the validity of this new frequency discriminator a prototype of the tunable dual-mode microstrip resonator has been designed and fabricated. Then, the measured results have been used to study the complete frequency discriminator performance. Obtained results show that the proposed varactor-tuned dual mode frequency discriminator covers almost an octave of frequency range from 1.05 to 2 GHz with a good sensitivity for the first mode (better than 45 V/GHz) and the second mode (better than 21 V/GHz) that can be clearly improved in future implementations.

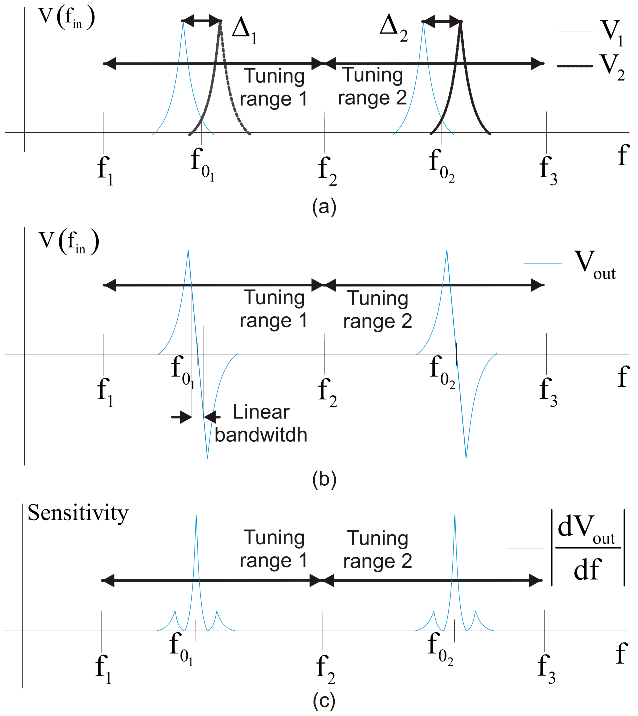


Fig. 2. Working principle of the varactor-tuned dual-mode frequency discriminator. a) Frequency response at the power detector output. b) Frequency response at the differential amplifier output. c) Sensitivity.

II. DUAL-MODE FREQUENCY DISCRIMINATOR

The block diagram of the proposed frequency discriminator is shown in Fig. 1. This architecture makes use of a 180º hybrid coupler (instead of the traditional transformer [7]) to split the input signal between the dual-mode resonators. After being filtered, the power of the input signal is measured by two detectors obtaining two DC Voltages (V_1,V_2) that depend on the frequency and the power of the signal with a frequency response as the one shown in Fig. 2(a). Finally, these DC signals (V_1,V_2) are amplified and subtracted obtaining the frequency response shown in Fig. 2(a). This response presents two main slopes that cross over zero at the frequencies f_{01} and f_{02}. In the proximity of these frequencies (f_{01}, f_{02}) there is a linear Voltage-to-frequency dependency ($V_{out}(f_{in})$) and the circuit acts as a linear frequency discriminator. The main novelty of the new proposal is that for each bias Voltage (V_{DC}), the dual-mode frequency discriminator can work in two different frequency bands close to f_{01} and f_{02}. Furthermore, the resonators can be designed making use of two different bias Voltages to control the tuning of the second frequency range independently. This potentially doubles the covered frequency range when compared to the classical approach without significantly increasing its complexity.

The accuracy of this technique depends on the normalized sensitivity of the discriminator around the frequencies f_{01} and f_{02} (see Fig. 2(c)), defined as

$$\text{Sensitivity} = \frac{1}{G_1 G_2}\frac{dV_{out}(f)}{df}\ , \qquad (1)$$

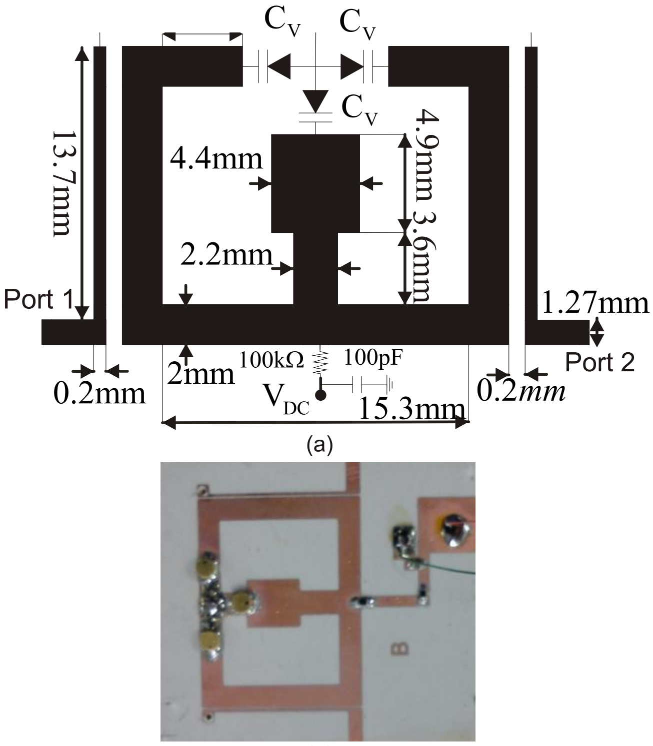


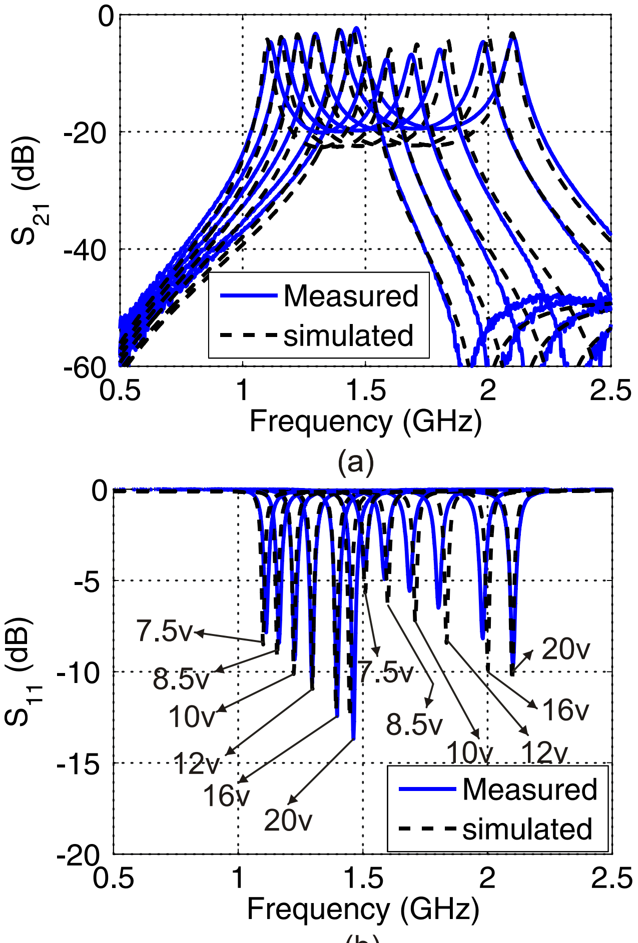
Fig. 3. a) Layout out of the proposed dual-mode resonator on a RO3003 0.5-mm-thick dielectric substrate with a relative dielectric of 3. b) Photograph of the fabricated prototype (26x25mm^2).

where G_1 and G_2 are the gains of the amplifiers used at the output of the power detectors.

This sensitivity is mainly fixed by the Q factor of the resonators and the difference between their resonant frequencies (Δ_i). Both resonators must have their resonant frequencies slightly shifted in all their tuning range to detect any frequency inside their operational bandwidth (see Fig.2(a)). There are two main options to adjust the relative difference of their resonant frequencies (Δ_i), i) designing two different resonators that can be controlled by the same bias Voltage (V_{DC}), as in Fig. 1, or ii) designing only one resonator but with a different bias Voltage in each branch of the frequency discriminator. In this paper, this second strategy will be used to study the performance of the discriminator.

III. VARACTOR-TUNED DUAL-MODE RESONATOR DESIGN

The tunable dual-mode resonators are the key elements of the new frequency discriminator. They determine the maximum tuning range and sensitivity that this structure can achieve. It is important to design these circuits with a sufficient quality factor in order to increase the slopes around their resonant frequencies, and adjust the relative difference between the resonant frequencies of both resonators (Δ_i) in the tuning range to maximize the sensitivity of the discriminator.



(a)

(b)

Fig. 4. Measured and simulated S-parameters of the designed tunable dual-mode resonator for different bias Voltages between 7.5-20V. a) Insertion loss (S21). b) Return loss (S11).

Several resonator topologies can be modified to obtain the two different modes with a single resonator such as the open-loop resonator [9], the ring resonator [10], etc. Figure 3(a) shows the layout of the designed microstrip tunable dual-mode resonator based on the open-loop topology and similar to the one studied in [9], but for the new application as proposed. It makes use of three MA46H203 varactors [11] and a single dc-bias circuit to control the tuning of both modes that do not coupler each other. In our proposal each mode is used independently to cover two different frequency ranges, making the design procedure very simple: i) first, the external open-loop microstrip line connected to two of the varactors is designed to control the first mode (even mode), ii) secondly, the central stubs connected to the third varactor are designed to adjust the performance of the second mode (odd mode) without affecting the even mode, and iii) finally, the external coupled lines are designed as broadband transformers to uncouple the resonator from the input lines and improve its quality factor. The final dimensions of this circuit are included in Fig. 3(a).

A prototype of this circuit has been manufactured with Rogers 3003 substrate (500μm thickness, $\epsilon_r = 3$), obtaining a total size lower than 26x25mm^2. Its photograph is included in Fig, 3(b). This circuit has been measured for different bias Voltages in the range of 6 to 20V. Some of these results are shown in Fig. 4. This figure shows a good agreement between the measured and the simulated results with the resonant frequencies perfectly covering the frequency range from 1.1 to 2.1 GHz. The most significant difference is that the rejection in the band between the resonant frequencies is worse than expected due to the extra coupling caused by a poor etching in the external coupled lines.

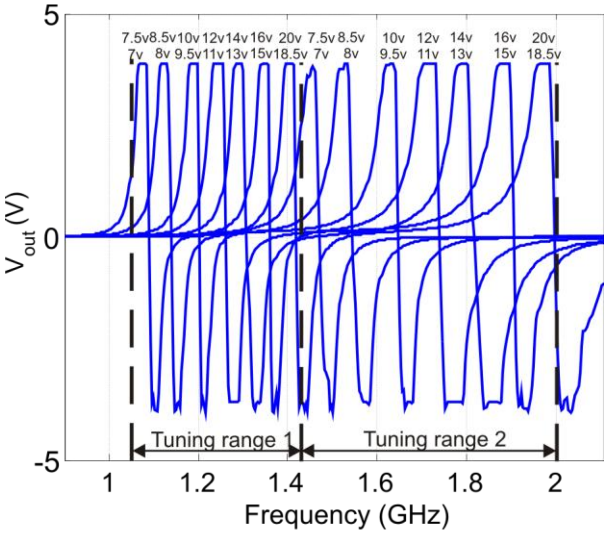


Fig. 5. Output Voltage of the dual-mode frequency discriminator for different bias Voltages between 7-20V.

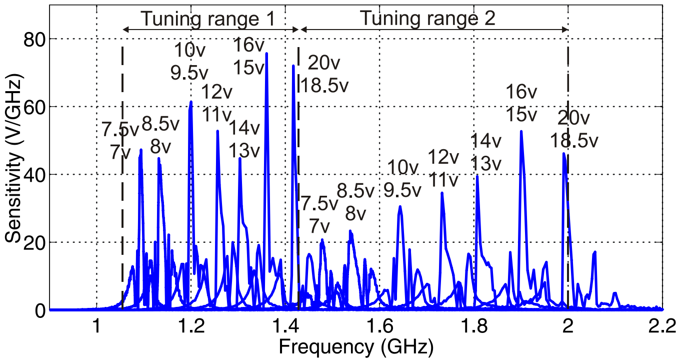


Fig. 6. Sensitivity of the dual-mode frequency discriminator for different bias Voltages between 7-20V.

IV. FREQUENCY DISCRIMINATOR

The proposed frequency discriminator has been designed using the block diagram shown in Fig. 1 and the measured results of the dual-mode resonator for different bias Voltages. The remaining elements used in this study are: i) a 180º hybrid coupler ii) two Avago HSCH-9161 based detectors [12], and iii) three Texas Instruments operational amplifiers OPA656 with a gain of 8V/V [13]. In this configuration the detectors speed is mainly fixed by the demodulation bandwidth at the output of the power detectors. This bandwidth is usually controlled by the video resistance (R_v) of the power detectors and the input capacitance of the operational amplifiers, obtaining typical values around 50-100 MHz.

The output Voltage of the frequency discriminator for different pairs of bias Voltages is shown in Fig. 5. As we can see it achieves the response theoretically explained in section II and depicted Fig. 2(b). Besides, the sensitivity of the frequency discriminator for the same pairs of bias Voltages is shown in Fig. 6. A sensitivity better than 45 V/GHz and 21 V/GHz for the first and second mode, respectively, is observed for the complete tuning range from 1.05 to 2 GHz. Besides, these values can be enhanced by adjusting the bias Voltages to get a more uniform response. The lower sensitivity of the second band is mainly caused by the poor etching, as commented in section III, and the lower return loss measured for the second mode of the resonator (see Fig. 4(b)), and can be clearly improved in future designs.

The simulation performed in this section has demonstrated, at the first time, that it is possible to increase the bandwidth of the classical approach [7] using tunable dual-mode resonators to cover two different frequency ranges, making the design of ultra-compact broadband frequency discriminators realizable. Besides, the obtained results can be clearly improved designing the relative difference of the resonant frequencies (Δ_i) to optimize the sensitivity in the complete frequency range, or even using different dual-mode resonant structures.

V. CONCLUSION

In this paper a novel varactor-tuned dual-mode frequency discriminator has been studied. It makes use of two non-interacting tunable dual-mode microstrip resonators potentially doubling the frequency range of the classical approach and making feasible the design of ultra-compact broadband frequency discriminators. Measured results of fabricated dual-mode resonator show an octave tuning range covering the 1.05 to 2 GHz band.

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