Microwave Interference Techniques for Frequency Measurement and Filters

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Abstract—This paper reviews the application of microwave signal-interference techniques to interferometers for frequency measurement and filters. The microwave interference takes place when the input-signal components pass through two different electrical paths to be then recombined and produce an interference pattern. Path lengths define the interference-based power-transmission maximum and minimum, which are calculated to obtain the desired device frequency response. Reconfigurable interferometers, wide-band, and dual-band filters designed using interference principles are described in this overview paper.

Keywords—interferometer, instantaneous frequency measurement (IFM), filter, microstrip devices

I. INTRODUCTION

The microwave interference principle consists of dividing an input signal in two components that propagate through two different electrical paths before being recombined at the output. Since the divided signals have the same frequency, the lengths of the paths mostly determine the phase difference between them; when the signals are combined, constructive and destructive interferences occur, creating an interference curve. The frequency of the minima and maxima are spectrally periodic, as defined by the medium properties and the lengths of the uniform-impedance transmission-line paths.

Microwave interference is useful to design microwave devices with filtering properties, such as interferometers for frequency measurement applications [1-4], wide-band [5, 6] and dual-band [7] bandpass filters among others. The core part of these devices is the interferometer section. Delay lines connect to power dividers/combiners or direct to a T-junction constitute a microstrip interferometer, so that the electrical length and characteristic impedance of the delay lines are the parameters used to define the device frequency response.

This paper reviews frequency measurement methods and filters based on signal-interference techniques. Section II describes two mathematical techniques to calculate transmissions zeros of an interferometer section. Section III provides examples of devices designed using the microwave interference technique. The first devices use interferometers to design reconfigurable frequency measurement (RFM) systems. In the RFM system, switches select signal paths with different lengths, providing different interference curves used for unknown frequency identification. The unknown signal will fall into a set of sub-bands after properly choosing a threshold level and adding an A/D conversion stage. The whole system provides a digital word, associated with a given sub-band where the unknown signal is located. The second type of devices are ultra-wide band (UWB) and dual-band filters. The signal-interference technique allows highly-selective bandpass transfer functions with sharp-rejection stopbands to be realized [5]. Here, to obtain a UWB and dual-band response with increased out-of-band rejection levels, interferometers are placed in cascade and the characteristic impedance of the delay lines and their lengths are design parameters. Finally, section IV provides an overall conclusion for this work.

II. MICROWAVE INTERFERENCE THEORY

This section describes two mathematical techniques to calculate the electrical length and/or characteristic impedance required to obtain a desired signal-interference pattern. Fig. 1 shows the diagrams of a typical microwave interferometer. The structure consist of two transmission lines connected by a divider/combiner (Fig. 1(a)) or directly connected in a T-junction (Fig. 1(b)).

The first technique consists of analyzing the signal in time domain, where each delay line provides a different delay time \( t_0 \) and \( t_n \). Considering an input sinusoidal signal \( x(t) = \sin(\omega t) \) in Fig. 1(a), the combined delayed signal is given by (1), where the distance between two consecutive maxima or minima in the interference curve is given by (2). Thus, the minima or maxima are located by properly choosing the electrical length of each delay line.

\[
s(t) = \frac{A}{2} \cos\left(\frac{\omega(t_n-t_0)}{2}\right) \sin\left(\frac{2\omega t - \omega(t_n+t_0)}{2}\right)
\]

1. Diagram of a microwave interferometer transmission-line-based path connected to a (a) power divider/combiner and (b) T-junction. \( Z_2, \theta_2 \) is the line characteristic impedance; \( \theta_1 \) the electrical length; \( \ell_n \) the physical length and \( \ell_0 \) the delay time.

\[ s(t) = \frac{A}{2} \cos \left(\frac{\omega(t_n-t_0)}{2}\right) \sin \left(\frac{2\omega t - \omega(t_n+t_0)}{2}\right) \]
\[ \Delta f_{\text{max}} = \Delta f_{\text{min}} = \left| \frac{1}{\Delta \theta_{\text{si}}} \right| \]  \hspace{1cm} (2)

The second technique is based on calculating the location of frequency nulls by properly choosing the length and impedance of the delay lines when they are directly connected in parallel without input/output power divider/combiner (Fig. 1 (b)). The interference pattern is defined by analyzing the transmission through the interferometer topology in Fig. 1b, or \( S_{21} \), given in (3),

\[ S_{21} = \frac{-j\Delta f_{0} (Z_2 \sin \theta_1 + Z_3 \sin \theta_2)}{Z_0 + Z_2^2 (Z_2 \sin \theta_1 + Z_3 \sin \theta_2) + Z_3^2 (Z_2 \sin \theta_1 + Z_3 \sin \theta_2)} + Z_2 (Z_2 \sin \theta_1 + Z_3 \sin \theta_2) - j\Delta f_{0} (Z_2 \cot \theta_1 + Z_3 \cot \theta_2) \]  \hspace{1cm} (3)

where \( Z_0 \) is the port impedance. The transmissions zeros are obtained when \( |S_{21}| = 0 \), and will be present at frequencies at which condition (4) is satisfied.

\[ Z_2 \sin \theta_2 = -Z_3 \sin \theta_1. \]  \hspace{1cm} (4)

If \( \theta_{10} \) and \( \theta_{20} \) are, respectively, the electrical lengths of the interferometer at the center frequency \( f_0 \), then condition (4) can be written as (5).

\[ \frac{\sin((f_0/f_1) \theta_{10})}{\sin((f_0/f_2) \theta_{20})} = \frac{Z_2}{Z_3}, \]  \hspace{1cm} (5)

where \( f_2 \) is the transmission zero frequency.

III. MICROWAVE INTERFERENCE APPLICATIONS

The signal-interference technique described in previous section is used to produce a reconfigurable frequency measurement (RFM) system, wide-band and dual-band filters. The frequency measurement system is widely used for electronic warfare (EW), radar monitoring, communications and weapon guidance systems [1]. The RFM is an evolution of instantaneous frequency measurement (IFM) systems in terms of miniaturization, since it uses switches to select different signal paths. The signal-interference technique also presents a new approach to filter design with sharp-rejection stopbands. These highly-selective multi-band and wide-band filters are respectively applied in systems that support multiple standards at the same time [5] and broad-band receivers (e.g., wide-band EW, ultra-wideband radar and high data-rate communication systems [4]).

A. RFM

Fig. 2(a) shows a 2-bit RFM [2] circuit, where the reconfigurable interferometer is the main part of this design. The RFM uses a wideband power divider and combiner, a reference line \( l_0 \) and two delay lines \( l_1 \) and \( l_2 \). SPDT switches select one for two possible delay lines at a time, and combined with the reference line at the interferometer output. The delay lines \( l_1 \) and \( l_2 \) are calculated such that \( \Delta \theta_{0.2} \) is two times \( \Delta \theta_{0.1} \) (see eq. (2)). Fig. 2(b) shows the frequency response of the 2-bit RFM from 1 to 4 GHz. The PIN diodes D1 and D2 make up the SPDT 1 and, D3 and D4, form SPDT 2. The device switches between state 1 (line \( l_1 \) selected) and 2 (line \( l_2 \) selected). Dimensions of the complete device are as small as 45 mm x 65 mm. When the magnitude of the \( S_{21} \) parameter is above an arbitrary chosen threshold level at the A/D conversion stage, bit 1 is obtained; otherwise the system output is bit 0. The interference curves divide the interferometer frequency range of operation in 4 sub-bands, thus the system provides a 2-bit binary word that identifies an unknown signal.

In [4], an even more compact RFM interferometer is described. The interferometer delay lines are based on the Hilbert fractal curve, with space filling properties allowing to increase the delay line length in one overall delimited area. Fig. 3(a) shows the fractal based RFM device. The proposed RFM is composed by power divider/combiner, reference line and delay line based on the second Hilbert iteration. The diodes switch the interferometer producing three states, where \( l_1, l_2, l_3 \) are selected one at a time and combined with the reference line to produce the interference patterns. Fig. 3(b) shows the delay lines selected for each device state. The respective delay times in nanoseconds are approximately \( t_1 = 0.45, t_2 = 0.96, \) and \( t_3 = 1.53 \). Dimensions of the complete device are as small as 53 mm × 39 mm. Fig. 4 shows the interference curves after switching among all device states.

Fig. 2. (a) 2-bit RFM prototype. (b) 2-bit RFM frequency response. ARlon AD1000 substrate with a dielectric constant of 10.2, loss tangent of 0.0023, and dielectric thickness of 1.27 mm [2].

Fig. 3. (a) 4-bit RFM fractal-based prototype. FR-4 substrate with a dielectric constant of 4.3, loss tangent of 0.025, and dielectric thickness of 1.6 mm. (b) Delay lines corresponding to the three RFM states [4].

Fig. 4. Frequency response of the 4-bit RFM fractal-based prototype [4]; solid line, simulated results, and dashed line, measured results.
The interference curves divide the frequency range (2.7 to 4.5 GHz) in 8 sub-bands corresponding to a 3-bit binary word. This system identifies an unknown signal without ambiguity, and presents a miniaturized profile compared to the 2-bit RFM.

B. Filters

Microwave interference is used to produce a wide-band filter [5]. Using eq. (3) and imposing the power transmission maximum at the center frequency $f_0$, the relations to calculate the location of the first transmission zeros is: $Z_2 = (Z_1Z_0)/(Z_1-Z_0)$, $\theta_1(f_0) = m\pi$, $\theta_2(f_0) = (2n+m)/2\pi$; where $Z_i > Z_0$ and $\theta_i > 0$.

The wide-band filter is shown in Fig. 5. The filter is composed by two cascaded interferometers connected by a transmission line with a length of $\lambda_0/2$, and characteristic impedance of approximately $Z_0/2$. The filter design procedure starts with Section 1, which determines the overall filter pass-band bandwidth. The second step is determining Section 2, which together with a cascade connecting line, increases the stop-band rejection levels and sharpness around the pass-band edges.

Fig. 6 shows the frequency response of the filter and the transversal sections that satisfy a 28.5%, 3-dB relative bandwidth specification. The lines of the interferometer sections use the first iteration Sierpinsky geometry to decrease the surface area occupied by the filter. The measured results are in a good agreement with the simulated results [5] and a larger stop-band than a pass-band makes the filter suitable for multichannel and full-duplex communications.

In [7], the signal interference technique is used to design dual-band filters. Figure 7 shows the fabricated filter. To calculate the transmission zero it is necessary to take into account these follow conditions: 1) Generation of an interference transmission zero at a given frequency $f_0$; 2) Maximum power transmission at two adjacent-to-$f_0$ dual-band center frequencies $f_0$ and $f_{02}$; and 3) Spectral symmetry with regard to $f_0$ [7]. By applying these conditions in the analytical formula for the power transmission and reflection coefficients, two set of equations are derived to design the filter in [7]. Fig. 8 shows the simulated and measured results of the filter. The filter operates in two distinct bands at 1.4 and 2.6 GHz with bandwidth of 250 MHz. Three interferometer sections are arranged in cascade form to obtain the desired response. Three transmission zeros are generated approximately at frequencies 1.169, 2, and 2.831 GHz, producing sharp-rejection stop-bands. Note also that it is possible to achieve a wider rejection band by adding a cascaded band-stop filter for example.

IV. CONCLUSIONS

This paper reviews the signal interference technique applied to microwave devices. The interferometer is the core building element of the circuits and consists of power divider/combiner or direct T-junction and delay lines. Two mathematical expressions to calculate the parameters of the interferometer are provided, taking into account the length and characteristic impedance of the delay lines. Experimental demonstrators of RFM and filters using microwave interference are shown.

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