Frequency discriminator design phase formula with experimental verification for frequency measurement systems with uniform sub-band resolution

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Abstract
In this article, we propose a frequency discriminator (FD) design method to produce uniform frequency sub-bands. FDs are designed using an interferometer projected with the proposed formulated phase. For experimental verification that a uniform sub-band is formed using the proposed phase formula, 3-bit FDs are designed and fabricated to operate in the 2 to 3 GHz and 2 to 4 GHz bands, respectively. The FD consists of a power divider/combiner, reference line, and delay line. Scattering parameters of the FDs are analyzed using RF simulation and measurement results. RF characteristic results show that a 3-bit FD designed using the proposed phase formula can identify an unknown signal inside the defined frequency band.

KEYWORDS
frequency discriminator design, frequency measurement, interferometer, uniform sub-band bandwidth

1 | INTRODUCTION

In electronic warfare, detecting a collection of wireless signals secretly used by hostile aircraft, ship or vehicle is directly related to warfare victory. An instantaneous frequency measurement (IFM) receiver is a device that identifies the frequency of an unknown wireless signal and presents it as a displayable digital signal. Using this digital signal, friendly forces can acquire or predict enemy strategy, or jam enemy communication systems. Therefore, IFM receivers are essential devices for gaining an edge in electronic warfare.\textsuperscript{1}

An IFM receiver is comprised of antenna, limiting amplifier, frequency discriminator (FD), detector, and a digitizing circuit.\textsuperscript{2-5} In an IFM receiver, the FD plays an important role because it determines the sub-band associated to the bits of a binary number. If the determined sub-bands are uniform, an unknown signal can be identified as an ideal binary number. FDs are implemented in a variety of structures, such as interferometer,\textsuperscript{5,6} RF filter\textsuperscript{7,8} and frequency selective surface.\textsuperscript{9} An interferometer-based FD consists of two delay lines and a power divider/combiner. Sub-bands are formed according to the phase difference between the two delay lines causing mutual interference. The phase difference can be formulated to produce uniform sub-bands for frequency identification. Recently, reconfigurable frequency measurement (RFM) receivers using phase shifters\textsuperscript{10-13} have the advantage of low-power consumption and miniaturization because fewer electronic components are required, compared to IFM receivers. The formulated phase differences are useful for the FD design and implementation.

In this article, we first propose a phase formula for FD design with uniform frequency sub-bands. Each phase of the FD can be obtained using the proposed phase formula if the desired sub-bands are uniform and the desired frequency is identified.
resolution is known. A set of fixed-FDs is fabricated for the experimental verification. The proposed phase formula is successfully verified by simulation and measurement results. The results show that the desired frequency bands can be divided into uniform sub-bands for frequency identification.

2 | PHASE FORMULA FOR UNIFORM SUB-BANDS

To obtain the ideal binary representation of the input signal, the phase formula of the FD is derived using the time delay \( \tau_{d,n} \) of the \( n \)th discriminator. As in Reference 2, \( \tau_{d,n} \) is given by

\[
\tau_{d,n} = \frac{1}{4f_{r,n}},
\]

where \( f_{r,n} \) is the sub-bandwidth of the \( n \)th discriminator. For uniform partition of the desired frequency identification band, \( f_{r,n} \) is expressed as follows:

\[
f_{r,n} = \frac{BW}{2^n},
\]

where, \( BW \) is the desired frequency identification bandwidth, and \( n \) is the number of bits of the binary digital signal. An FD requires an \( S_{21} \) magnitude-frequency characteristic obtained via constructive and destructive signal interference adjustments, as shown in Figure 1. The interval \( (f_{int,n}) \) between consecutive transmission zeros or the point at which the signal is canceled is expressed as the inverse of \( \tau_{d,n} \). Using Equations (1) and (2), the interval can be obtained as follows:

\[
f_{int,n} = \frac{1}{\tau_{d,n}} = \frac{BW}{2^n - 2}.
\]

For the \( n \)th discriminator, the phase difference between the reference line and the delay line is expressed by dividing the angular frequency into the interval between the consecutive transmission zeros.

\[
\Delta \phi_{n,0} = \phi_n - \phi_0 = \frac{\omega}{f_{int,n}} = \frac{2\pi f_c}{f_{int,n}},
\]

where, \( \phi_n \) is the delay line phase for the \( n \)th discriminator at the center frequency \( (f_c = f_{min} + BW/2) \), \( \phi_0 \) is the phase of the reference line at \( f_c \). \( f_{min} \) is the minimum

FIGURE 1 | \( S_{21} \) magnitude-frequency characteristics of a 3-bit FD with uniform sub-bands

FIGURE 2 | Interferometer-based FD schematic diagram

FIGURE 3 | Photograph of the fabricated 3-bit FDs. A, FD with coefficient \( k = 1 \). B, FD with coefficient \( k = 2 \)
frequency in the frequency identification band. Substituting Equation (3) into Equation (4), results in:

$$\Delta \phi_{n,0} = \pi \left( \frac{f_c}{BW} \right) 2^{n-1} = \pi \left( k + \frac{1}{2} \right) 2^{n-1}, \quad (5)$$

where, $k$ is the coefficient defined using BW and $f_{\text{min}}$, and expressed as $f_{\text{min}}/BW$. Equation (3) holds only under the conditions that $k$ is a natural number. If only the desired BW and frequency resolution are known, it is possible to define the delay line phase required for a set of FDs that produces a uniform sub-band resolution for frequency identification, by using Equation (3). The group delay of the reference line and delay line has a constant value other than zero.

### 3 | FD DESIGN USING PHASE FORMULA

For the verification of the proposed phase formula, a typical fixed-FD based on interferometer was designed using the proposed phase formula. A fixed-FD consists of power divider/combiner, reference line, and delay line (See Figure 2). The signal path through a fixed-FD is as follows: First, the input signal is separated into two signals of equal power level at the power divider. The two separated signals are delayed with phases $\phi_0$ and $\phi_n$, respectively, according to the reference line and delay line and then combined at the circuit output.

Two 3-bit fixed-FDs are designed operating from 2 to 4 GHz and 2 to 3 GHz with a $k$ of 1 and 2, respectively. The characteristic impedance of the reference and delay lines is matched to 50 $\Omega$ using microstrip lines. Copper and FR-4 ($\varepsilon_r = 4.4, \tan\delta = 0.02$) are used as conductor and substrate, respectively. The phase of the reference line is delayed by $0.5\pi$ radians at each $f_c$. The delay lines for 3-bit identification from 2 to 4 GHz have the phase delayed by $2\pi$, $3.5\pi$, and $6.5\pi$ for each bit, respectively. For the delay lines used in the 3-bit fixed-FD operating from 2 to 3 GHz, the phase is delayed by $3\pi$, $5.5\pi$, and $10.5\pi$ for each bit, respectively.

### 4 | RESULTS

Figure 3 shows the fixed-FDs fabricated using a 1 mm-thick FR-4 substrate. Copper with a thickness of 50 $\mu$m was used as signal line and ground plane. A 100 $\Omega$ chip
A resistor is used in the power divider/combiner. The length of the delay lines is determined using the phase formula, corresponding to each bit. The $S_{21}$ characteristics of the fixed-FDs are measured using a SOLT-calibrated Agilent HP 8753D vector network analyzer (Agilent Technologies Inc., Santa Clara, CA) and compared with simulation results using ANSYS HFSS (Ansys Inc., Canonsburg, PA).

The simulated and measured results are in good agreement, as shown in Figure 4. However, measurement results (solid line) were uniformly slightly shifted to 40 to 45 MHz toward lower frequencies, relative to the simulation results (dash-dot-dot line). The $S_{21}$ magnitude-frequency characteristic shift depends on substrate dielectric constant, substrate thickness and the dimensions of the microstrip lines, etc. The dielectric constant of FR-4 used as substrate varies from 1 to 10 GHz, in a range from 4.4 to 4.6, depending on the manufacturer and frequency of operation.

Figure 5 shows the simulation results (dash-dot-dot line) using FR-4 with 4.6 dielectric constant and measurement results (solid line). It is assumed that the FR-4 material used has a dielectric constant close to 4.6. The simulation results agree well with the measurement results. The desired frequency bands can be coded as 3-bit binary numbers, considering a threshold of $-3.8$ and $-3.9$ dB, respectively. The simulation results using the FR-4 substrate with 4.6 dielectric constant has a standard deviation (SD) within 14% of 250 MHz for the 1.955 to 3.955 GHz design. From measurement results, the SD is within 12% of 250 MHz from 1.955 to 3.955 GHz. In the band from 1.96 to 2.96 GHz, the simulation results have a SD within 17% of 125 MHz. In measurement results, the SD is within 20% of 125 MHz. Table 1 shows the sub-bands, the SD and the dimensions of the fabricated fixed-FDs. The size of the fixed-FD increases as the delay line gets longer, in proportion to the phase delay. The SD of the sub-bands increases as the frequency identification resolution increases. Losses in the high-frequency bands caused by FR-4 substrate distort the $S_{21}$ magnitude characteristics, making it difficult to divide the frequency identification bands uniformly. In addition, losses in the resistor chip or SMA connector soldering may also contribute to the slight variations in simulation and measurement results.

The proposed FD design method using the phase formula is experimentally verified using simulation and measurement results in this work. Although the SD of the 3-bit FDs increased significantly, it is clearly shown that a FD can be easily designed using the proposed phase formula. The proposed FD design method is also useful if the delay lines occupying most of the physical area of the FD are designed using a phase shifter. Furthermore, digital processing can be used to extract the unknown frequency in a full IFM receiver.

## 5 | CONCLUSION

In this article, we designed and fabricated an interferometer-based FD after formulating its required phase delays. The validity of the proposed formula is examined by simulation and measurement for two frequency bands, 2 to 3 GHz and 2 to 4 GHz, respectively. The design method provides the phase required to produce uniform sub-bands for frequency identification when the bandwidth and number of bits are known.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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