Review of Microwave Frequency Measurement Circuits

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Abstract: In this work, microwave frequency measurement (MFM) is reviewed since the early stages using fully analog implementations, including its evolution to analog/digital implementations with high resolutions up to 1 MHz. The review includes fully digital implementations and microwave photonics techniques, with a discussion on achieved devices and the overall field of measuring and identifying unknown signals. MFM plays a crucial role in electronic warfare, communications, and electronic intelligence systems by identifying the frequency of unknown signals. Several microwave planar devices such as interferometers, filters, and frequency selective surfaces have been proposed to design low-cost and low-power digital MFM systems. The planar devices presented here show resolutions from 1 MHz to 940 MHz and operate in the frequency range from 0.15 GHz to 11.5 GHz, having typical bandwidths from 1 GHz to 2 GHz. MFM using microwave photonics techniques involve mapping the microwave signal into the optical spectrum to create a frequency-power function, that uniquely identifies the frequency of the unknown signal, with large bandwidths and immunity to electromagnetic interference.

Keywords: Microwave devices, frequency measurement, planar devices, microwave photonics.

1. Introduction

Microwave Frequency Measurement (MFM) systems receive an unknown signal and swiftly identify its frequency. MFM has been widely used for electronic warfare, radar monitoring, communications, weapon guidance systems and electronic intelligence systems, presenting high accuracy, and high probability of intercepting over wide Radio Frequency (RF) bandwidths [1-5].

In a previous review paper [2], the author presents the development of Instantaneous Frequency Measurement (IFM) over 50 years, before 2012, showing the performance principle of early (analog) IFM systems using coaxial cables until the all-digital IFM systems using Field-Programmable Gate Arrays (FPGA). However, new devices for IFM systems are not covered in [2], including Microwave Photonics (MP) techniques, reconfigurable frequency measurement, and recent planar implementations with filters or Frequency Selective Surfaces (FSS).

This paper provides an overview of recent advances in MFM using electronic planar devices like filters, delay lines, and FSS, as well as MP and digital techniques, including an overview of recent designs and their performance, advantages, and drawbacks.

A generalized conventional MFM system consists of limiters, amplifiers, power dividers, discriminators, detectors, and Analog to Digital Converters (ADC). MFM is traditionally implemented using electronic components and classified as fixed or reconfigurable designs. Fixed designs have a predefined number of frequency discriminators with an associated resolution and frequency of operation. They can be implemented using delay lines [6-19] using planar or coaxial transmission lines, or filters [20-29]. Discriminators based on filters and delay lines are designed to produce a frequency response associated with Gray's code, obtained after the ACD stage [30]. High-resolution designs may require many discriminators, usually one discriminator per bit, the combination of using microwave analog discriminators and digital signal processing, results in analog/digital designs with high resolutions and has been common practice over the years. Reconfigurable frequency discriminator designs use switches to select between different delay lines and it just requires at least one reconfigurable discriminator. The reconfigurable discriminator requires fewer electronic components, uses less space, and operates with less power consumption, due to the use of reduced components compared to instantaneous implementations. Continuously tuned MFM also can be performed using varactor diodes [31].

With the continuous development of digital circuits together with fast sample-and-hold circuits, the frequency measurement position of conventional MFM receivers has been challenged by circuits completely digital [2]. However, the clock of the circuits is still a limitation to the operational band of fully digital MFM, as an example, an IFM digital receiver available in Teledyne Corporation [32] can identify signals in a frequency range from 0.5 to 2.4 GHz. In a recent paper [33], the authors achieved an instantaneous band identification of 5 GHz applying multichannel sub-Nyquist sampling with a maximum of 0.8 MHz RMS error. The analog/digital receiver, that mixes RF devices and an FPGA can measure frequencies from 2 to 18 GHz with high accuracy.

MFM performed with MP techniques operates in a wide frequency range from 0.6 to 42.8 GHz [34-45]. Frequency-amplitude mapping is the most effective method to obtain the unknown microwave signal`s frequency. In this method, the microwave frequency is converted into optical or microwave power [37]. The Photodetectors (PD) and ADC circuits provide the reading of the unknown signal. MP has the advantage of having a high frequency of operation with large bandwidths, low loss, and immunity to electromagnetic interference [37-44].

The purpose of this article is to review the development of recent MFM devices, explain their fundamental principles and discuss designs through characteristics or performance comparisons. The paper is organized as follows. Section 1 contains MFM system principles. Section 2 presents microwave discriminators mostly used in MFM. Section 3 shows a classification of MFM made into four groups: analog, analog/digital, digital, and microwave photonics. Section 4 shows and describes specific devices according to the proposed classification. Section 5 discusses MFM challenges and suggests future research directions. Finally, conclusions of this work are summarized in Section 6.

2. MFM System

A generalized MFM system using electronic components is shown in figs. 1 and 2. The first stage is a receiving antenna. This device must satisfy specific requirements e.g., bandwidth, gain, polarization, axial ratio to ensure correct signal reception.

The second stage is composed of a limiter or a gain control circuit at the input of the frequency discriminator. A limiter amplifier is usually used as the solution to both dynamic range and sensitivity requirements. When a limiting amplifier receives low power input signals with power levels below a defined threshold, these signals are amplified in a traditional way, but when this device receives high power signals and their power levels reach the defined threshold level, the output of the amplifier will not be increased, but will stay at a constant level. In this way, the discriminator does not overdrive.

The third stage is formed with a power divider that equally splits the input signal into two or more output signals, while a power combiner receives two or more input signals and combines them as an output signal.

The fourth stage is formed by a microwave discriminator. This device is based on the principle of interference between two microwave signals. These signals are called the reference signal (RS) and delayed signal (DS). The principal difference between these signals is that the DS presents a delay which is a multiple of the RS delay. This difference produces a phase difference observed at the discriminator output signal, which is directly proportional to the unknown frequency. Assuming no phase modulation, this technique approximates the true instantaneous frequency as the delay approaches zero.

The fifth and sixth stages are composed by a detector and an amplifier, respectively. The detector converts the microwave power into electric power that is amplified before being introduced to the ADC stage. In the seventh stage, by properly choosing a reference level in the ADC, a binary word is obtained representing the frequency sub-band where the unknown signal falls into without ambiguity. The microcontroller in the eighth stage associates the binary word with the frequency sub-band. Interferometers and filters can be used to form microwave frequency discriminators. Fig. 1 shows a typical discriminator frequency response. To increase the resolution of a fixed system, it is necessary to increase the number of discriminators, where traditionally one discriminator corresponds to one bit for frequency identification.

Power dividers/combiners and delay lines compose the microwave interferometers. The microwave interference signal obtained from the differential delays on each frequency discriminator is used to identify unknown signals. Delay lines have been implemented in stripline or microstrip [1,2,11-13,15,18], coplanar [1,6,14,19], and coaxial transmission lines [7,8]. The digital code which uniquely identifies the unknown input signal over the bandwidth of the device, is formed by choosing the length of the delay lines on each microwave discriminator correctly. Because the device topology is parallel in nature, the frequency of any signal at the input is measured even if it is rapidly changing in frequency.

Low-pass, band-pass, and multi-band filters can be used to produce the frequency response required for frequency identification, as shown in fig. 6a. The filter response is used to mimic the interference pattern obtained using interferometers.

MFM based on delay lines or filters requires several discriminators to achieve high resolution, which implies a large overall system dimension. Reconfigurable delay line discriminators are proposed in [12-13,15]. A reconfigurable design is depicted in fig. 2, where just one discriminator, detector and amplifier are required, resulting in low power consumption compared to fixed designs (see fig. 1). PIN diodes are used to select the delay lines [12-13]. The reconfigurable MFM circuit is not in a parallel configuration such as the fixed one. Before providing frequency identification, it must switch among all its states. Fractal delay lines are an alternative to design even smaller fixed or reconfigurable devices for MFM [15-17] due to their space filling properties.

Reconfigurable band-stop filters [46-48] can be used to design reconfigurable frequency discriminators based on filters.

Fig. 3 shows the schematic diagram of a generalized MFM based on microwave photonics techniques. A light source, an electro-optic (EO) modulator, a photonic processing module, an optical-electrical (OE) conversion, and a post-processing circuit block compose the system. An unknown microwave signal is inserted into the EO modulator that has a wavelength carrier provided from a light source. Then, the modulated optical signal carrying the microwave signal is applied to the photonic processing module. After OE conversion and the post-processing module, the frequency of the unknown signal can be obtained [45].

Fig. 4 depicts a reconfigurable MFM implementation based on MP. The Mach–Zehnder modulator (MZM) and the dual-parallel MZM (DPMZM) modulate the unknown microwave signal with two independent wavelengths, from the laser diodes LD1 and LD2. After the signals pass through the dispersive medium, separated by two optical tunable filters at the photodetectors' output, the Amplitude Comparison Function (ACF) of the two power-fading characteristics can be constructed to provide the frequency-to-power mapping. It is possible to change the operating frequency of the system by tuning the bias of one of the three MZM that make up the DPMZM [34].

Fig. 5b shows the typical ACF curve response of an MFM based on MP. The fixed design has only one associated ACF curve. For the reconfigurable designs, the ACF can change according to a bias voltage (V_a, V_b, V_c, and V_d) applied to an MZM. The system identifies the unknown frequency without ambiguity until the first notch, which determines the operation band of the system ($\Delta f(V_a)$ for V_a, for instance) [34]. Each ACF curve in fig. 5b corresponds to a specific bias voltage used in reconfigurable designs.

3. Microwave Frequency Discriminators

This section presents an overview of the principal MFM discriminators used for analog, analog/digital and microwave photonic implementations. Discriminators based on delay lines use the microwave interference principle, which consists of dividing an input signal into two components that propagate through two different electrical paths before being recombined at the output.

The different paths delay the signal and when combined, constructive and destructive interferences occur, used for frequency measurement. Fig. 6 shows the diagram of a typical frequency discriminator based on delay lines, also called an interferometer. The junction can be Wilkinson dividers/combiners or T-junctions. The delay can be calculated using time domain when dividers/combiners are used. Consider an input signal x(t) = sin (ωt), after delay and recombination, the output signal is given by eq. (1).

$$s(t) = \frac{1}{2}\sin(\omega t + \omega\tau) + \frac{1}{2}\sin(\omega t + \omega\tau_1) = sin\left[\frac{2\omega t+\omega(\tau+\tau_1)}{2}\right] cos\left[\frac{\omega(\tau-\tau_1)}{2}\right], \quad (1)$$

where τ and τ_1 are the delays from the reference line and the delay line, respectively. From eq. (1), the frequencies where the maximum and minimum occur are given by

$$f_{max_n} = \frac{n-{}^1/_2}{\tau-\tau_1}, \quad f_{min_n} = \frac{n}{\tau-\tau_1}, \quad (2)$$

Here, n is an integer greater than zero. To avoid identification ambiguity, first determine the bandwidth (($\Delta f = f_{max_n} - f_{min_n}$, see fig. 5a), the central frequency of operation, and the frequency resolution. The resolution is given by eq. 3.

$$Resolution = \frac{\Delta f}{2^{n_d}}, \tag{3}$$

where n_d is the number of discriminators.

When using direct T junctions, the number of transmission zeros are calculated as a function of delay line electrical length and characteristic impedance. More details about zero calculation can be found in [49] where a six-pass band filter designed using signal-interference techniques is demonstrated.

The interference pattern using delay lines can be projected for a given bandwidth and resolution, with uniform sub-bands for frequency identification by using the formulas available in [50].

Discriminators based on filters can be designed using resonators that are coupled or attached to a transmission line. The filters present a band-stop frequency response with sharp-rejection transitions due to the resonator high loaded quality factor. The resonators can assume the geometry of meander lines, square and circular spiral, or rectangular loop as shown in fig. 7a. The rectangular loop resonates at frequencies where approximately $\lambda_g = \ell/2$, where ℓ is the resonator length, and λ_g is the signal guided wavelength. If the resonators are separated far enough from each other, to avoid couplings between them, the stop-band filter can be designed using several loop resonators as shown in fig. 7b, the typical resonator filter response used to form a frequency discriminator is shown in fig 7c. The coupling matrix can also be used to take the couplings into account [20]. Equations to calculate the resonant frequency of square and circular resonators can be found in [23].

The resonant frequency periodicity of the resonators is used to design a multi band filter for high resolution systems, as demonstrated in [23] and [24]. The filters can replace early lengthy, heavy, and bulky coaxial delay line implementations [2,7,8].

Fig. 8a shows two FSS designed to have a filter response, such as the one illustrated in fig. 8b. The band-stop FSS consists of dipoles (black strips) on the substrate. The dipoles resonate when their length is half-wavelength. Thus, the signal around the resonant frequency does not pass through the FSS. The MFM system based on FSS has the same scheme as figs. 1 and 2 and needs ultra-wideband (UWB) antennas to capture the signal after the FSS stage (see fig. 8c). The UWB antenna is connected to the detector to map the microwave input power in electric output power.

Discriminators implemented using MP generate a function to map the frequency of the unknown signal into electric power and provide an ACF. They consist of a light source, an EO modulator, a photonic processing module and an OE converter (see fig. 3). Fig. 9 presents an architecture that uses a comb filter with a sinusoidal response. The unknown microwave signal is modulated by the MZM with two wavelengths that come from Continuous Wave (CW) laser sources, and the filter weights more one optical frequency carrier than the other one. The resulting signal passes through a demultiplexer and then detectors. The ratio between the two PD outputs provides the ACF for frequency identification.

4. Frequency Measurement Devices

The review of MFM circuits presented here is classified into analog, analog/digital, digital and microwave photonics. Figure 10 presents the proposed classification of MFM devices, with examples. This section reports on several recent developments included in the proposed classification.

4.1 Analog (AMFM)

The first MFM receivers were completely analog. They mapped the frequency into a frequency-dependent parameter [2]. Despite being demonstrated more than 50 years ago, the analog MFM is still being currently used in Microwave photonic techniques [1].

4.1.1 Coaxial ring

In 1947, the coaxial ring or rat-race 3 dB hybrid was described by Tyrrell [51]. This design used the operating principle of coaxial delay lines. When the frequency of an input signal is equal to the design frequency, the power that entered in port 1 is divided equally in phase between ports 2 and 4. However, the power that entered in port 3 is equally divided but presents an offset of 180°. At different frequencies from the design frequency, both power level and phasing varied, therefore this behaviour limited the useful operating bandwidth to about 30%.

The rat-race design was the base for the early instantaneous frequency indicator. This design was implemented with a rat-race hybrid, a reference line, a delay line, and two square-law detectors (crystal diode).

4.1.2 Cathode ray oscilloscope

The first IFM receiver was introduced by Earp in early 1948 [52]. This receiver used polar coordinates on a scope to show the frequency of a measured signal. The fundamental operating principle of this device was based on splitting the input signal into two signals. Each signal flowed along a different electrical path. In one path, the phase of the signal was advanced by 90° at all frequencies, and in the other, the phase was retarded by 90° at all frequencies. As a result, the two output signals were anti-phase and produced a straight trace on an oscillograph screen when applied to the X and Y deflector plates of the cathode ray tube. This trace had different angular positions for different frequencies, the annular position angle is proportional to the frequency of the input signal and the amplitude of the trace is proportional to signal strength. This principle of operation suffered from shortcomings, the frequency scale of the oscillograph was not linear and the trace length varied over a wide range for constant signal input levels of different frequencies. Despite its drawbacks, some modern MFM receivers still use the same operating principle, but the frequency of the input signal is usually represented in digital format.

4.1.3 Waveguide

During the period from 1947 to 1952, waveguide components were used to build many microwave devices, e.g., discriminators, azimuth elevation prototypes, etc. The most useful applications of frequency discriminators are instantaneous frequency measurement receivers.

In 1949, R. V. Pound built the first microwave discriminator. It used a resonant cavity and two magic tees as a discriminator to stabilize a microwave oscillator. This discriminator was improved by Ashley [53]. Ashely's discriminator differs from Pound's circuit by separating the waveguide channels for the reflected signal from the cavity resonator and the reference signal for the phase detector. Thus, the discriminator's cavity resonator receives its signal from a three-port circulator instead of a magic tee or 3 dB hybrid. This change provides a total threshold improvement of 6 dB. In the late 1960s, James E. Secord built an MFM receiver that was implemented with a waveguide unit. This receiver operated up to 40 GHz with a bandwidth of 400 MHz [54]. The discriminator proposed by Nigrin [55] consisted of a single hybrid tee discriminator, a transmission line terminated by a moving short, and two crystal detectors coincident with the termination of the E and H arms of the tee. A similar microwave discriminator was proposed by Peebles and Green. This design operated at 35 GHz with a bandwidth of 400 MHz [56]. The device was implemented with a magic tee, a circulator, two line-matched detectors, one line length, and two shorts.

4.1.4 Switched stub

In the late 1950s, instantaneous frequency measurement receivers were developed primarily at three locations: Syracuse Research Corporation (SRC), Stanford electronic Laboratory (SEL) and Mullard Research Laboratories (MRL). From 1957 to 1958, SRC was working on the development of a switched stub technique for IFM receivers. This technique consisted of an RF switch that closed or opened after each input pulse. When the RF switch was opened, a shorted transmission line stub was inserted into the RF receiver, while in the opposite case, the line stub was not inserted. This behaviour affected the voltage standing wave ratio (VSWR) and the amplitude of the input signal. Thus, the variations could be related to the carrier frequency by means of a calibration chart [57]. This technique had a disadvantage, it was affected by pulse-to-pulse amplitude changes, generated by disturbances, and the pulse-pulse frequency agility could not be handled. Similar work developed by SEL is presented in [58].

In 1958, MRL presented the first operationally deployed MFM indicator. This MFM receiver used the principle of measuring frequency in terms of the phase delay of a signal propagating over a known length of transmission line. However, this receiver showed a new way of applying this principle in wideband receivers, i.e., the frequency of any received signal over an octave can be determined with an accuracy limited mainly by signal duration. This receiver did not use filters or other kinds of adjustment circuits [9].

4.1.5 Pulse Width Modulation (PWM) /Pulse Amplitude Modulation (PAM)

In 1962, SCR presented an early two-channel IFM approach [59]. This design consisted mainly of three sections: The first one was called the RF section. The second one was called the video data processing section, and the last one was called the data readout section. The RF section was implemented with two channels, i.e., this section used a power split to divide the input signal into two signals. Each signal flowed along a different path. One path had a frequency-sensitive element (e.g., shorted stubs) and the other did not. The second section was responsible for video data processing and signal conditioning, so it was implemented with some amplification stages. The data readout section used a pulse width modulation (PWM) or pulse amplitude modulation (PAM) process to encode the RF information into an-audio bandwidth signal. The RF output was encoded as a pulse duration. The device worked in the 50 to 250MHz band with a dynamic range of 15 dB and frequency accuracy of 13%. The device was 5.25 inches x 8.25 inches in size.

4.2 Analog/Digital MFM (ADMFM)

Several analog discriminators, such as delay lines and filters have been used to compose ADMFM. The main digitalization techniques use A/D converters, Arduino and FPGAs.

4.2.1 ADMFM based on delay lines

The Digital Fixed Implementation Technique (DFIT) based on delay lines needs a multiport discriminator to produce a bit for frequency identification, after the detection and conversion process [6-11, 14, 16-19]. They have been studied since 1996 [6]. If the delay lines are used to build an interferometer, the DMFM can present a large size due to the use of several electronic components to define a discriminator. This technique shows a high resolution of around 1 or 2 MHz [11] in some cases. In [18] an instantaneous frequency measurement receiver with a frequency resolution of 125 MHz is presented. This design can detect and measure continuous signals in the 4-6 GHz range using delay lines. The receiver has a 4-bit configuration. The accuracy of the instantaneous frequency measurement is improved by applying an offset voltage compensation to the comparator circuits, to compensate for the frequency dependent path loss of the delay line and the frequency dependence power detection. In [19] a device on a single 2"-LaAlO3 wafer with four bits for instantaneous frequency measurement is described. This superconducting design has a frequency of operation between 9.5 GHz and 10.5 GHz and uses coplanar $Y_1B_2Cu_3O_{7-\delta}$ delay lines and power dividers.

The reconfigurable discriminator was first proposed in 2014 with a 2-bit DMFM [12] design. Delay lines are used, where only one discriminator can produce an n-bit binary word [1],[12],[13],[15]. This results in a reduced number of electronic components for the whole frequency measurement implementation, independently of the number of bits, resulting in low power consumption [12-13]. In 2016, the authors increased the number of bits to 4 bits [13]. This technique shows an average resolution of 500 MHz [1,12,13,15]. The reconfigurable discriminator has a reduced size, due to the use of fewer electronic components and a two-port configuration. The drawback is that the frequency identification process is not instantaneous, since a switching time is needed to process all bits of a given design. In [13], the switching time required for frequency identification is 40 ns. A fixed size reconfigurable frequency discriminator using the space-filling properties of fractal structures is described in [15-17].

4.2.2 ADMFM based on filters

Multi-Band-Stop Filters (MBSF) have been used to produce frequency measurement circuits since 2008, as shown on the well-known methods described in [20, 21, 29] where half-wave rectangular open-loop resonators are placed near a transmission line to de-couple electromagnetic energy from the main transmission line, while other frequencies are able to go through the main transmission line. The resonance frequency is defined according to the resonator perimeter, the coupling distance between resonators, and the coupling distance between the resonators and the main transmission line. Each resonator defines a narrow reject band, so it is possible to design the resonators one by one to create the desired rejection bands in a more convenient way than with the delay line implementation. Due to the narrow reject band, the MBSF has a sharper frequency response transition, which leads to a more precise frequency identification avoiding errors in the ADC stage. This technique also presents a large size dimension, considering that a discriminator is necessary per bit for frequency identification, such as the implementation with fixed delay lines. In 2014, [27] microstrip frequency discriminators are used to produce a 5-bit instantaneous frequency measurement subsystem based on quarter-wavelength band-stop filters. The proposed 5-bit MBSF operates in a frequency range from 2 to 4 GHz with 62.5 MHz of resolution. Compared to implementations in [20,27,29], it presented a size reduction of 50%, while it remains with the same frequency range and resolution.

A 4-bit MFM subsystem based on band-stop filters connected to an Arduino board is presented in [60], 2015. The device shows the potential of producing micro-controlled low-cost MFM circuits with low weight.

In 2016, the balanced Gray code was used instead of the traditional Gray code implementation (shown in fig. 5a) [30]. Using the balanced grey code, sets of filters can be designed using the same amount of rejected sub-bands, while increasing the fractional bandwidth of filters. This technique is useful when considering high resolution frequency measurement based on filters, providing ease of fabrication, design, and implementation.

In [28], 2018, a 6-bit frequency discriminator based on microstrip filters is presented. The frequency response is shaped by using several rectangular and circular open-loop spiral resonators attached to the feed line, instead of coupled resonators. A unique 6-bit binary code determines the unknown frequency of the input signal with a resolution of 31.25 MHz and an error of 16 MHz in a frequency range of 2-4 GHz.

A 7-bit, high-sensitivity, compact size structure for instantaneous frequency measurement receiver is reported in [25], 2018. The proposed structure utilizes seven small-size, high-performance, microstrip band-stop filters to shape the frequency bandwidth based on binary division. The novelty here is that the output of each microstrip filter is divided into two paths, one with amplification and another without amplification to increase the dynamic range, according to amplifier gain. Based on measurement results, the proposed structure has -65 dBm sensitivity with about a 70-dB dynamic range for frequency detection. Also, the measured root-mean-square error is less than 35 MHz at the power level of -30 dBm. In other works, based on filters, this practical feature has not been considered.

In [23], 2018, a 7-bit frequency discriminator for instantaneous frequency measurement applications is described. The proposed discriminators are designed using microstrip band-stop rectangular and circular spiral resonators. Due to its periodic frequency response, it is possible to create equal sub-bands in the desired bandwidth with compact discriminators. Seven filters were used to compose the system that can identify frequencies from 2 to 4 GHz with 15.6 MHz of resolution.

The proposed structure in [24] uses open-ended resonators as the core part of the receiver, and is a continuation of the work in [23]. In [24], 15 compact frequency-shifted filters are designed to achieve high frequency resolution (12.5 MHz), instead of using the conventional Gray binary code frequency division. The Sensitivity and dynamic range of the proposed receiver are better than -65 dBm and 70 dB, respectively. Here, the authors used an FPGA to process the data with high-speed.

In [22, 26], 2017, a band-pass filter is used to produce a bit for frequency identification. The method proposed in [22, 26] is based on dividing the incoming RF signal into four signals and filtering them using an appropriate band-pass filter. The frequency is then estimated from the power level of the filtered signals. A closed-form for the standard deviation and the bias of the frequency discriminator is derived. This design operates in the frequency band from 2 to 4GHz. With just 4 filters and doing calculations of the closed-form equations using an FPGA, it was possible to identify frequencies with an accuracy of less than 15 MHz.

In 2020, [61] an 8-bit MFM system was presented. The authors have used the algorithm of Minimum Mean Square Error (MMSE) to estimate the signal frequency. The operating frequency of the IFM system is also from 2 to 4 GHz, however by using the MMSE algorithm it was possible to achieve an accuracy of 1.7 MHz, which is similar to commercial digital IFM. The proposed system was fabricated with an industrial-level technology using high-speed ADCs and the low-cost mid-performance FPGA (Xilinx Spartan-3EXC3S500E) as the digital processor.

Most discriminators based on filters exposed so far have proposed comparators or Arduino® to make the ADC based on a previously chosen threshold. As a result, the likely unknown signal frequency just depends on the sub-bands created by the discriminators, on the power of the incoming signal, and on the threshold level.

In 2021, the work in [62] describes a 15-bit IFM system that uses a different algorithm that considers not only the power of the incoming signal but also the imperfections that can arise in the manufacturing process. These imperfections take place by means of variations in substrate features (e.g. thickness and permittivity) and parasitic effects due to e.g. soldering, that cause a frequency shift or losses. In [62], calibration is made after the MFM fabrication process and assembly. The unknown frequency signal is compared with the binary code curve where the desirable threshold error can be adjusted. In contrast with [61], [62] presents lower accuracy of 11 MHz, however, the dynamic range is bigger and equal to 70 dBm.

4.2.3 ADMFM based on frequency selective surface

In 2018, a new frequency discriminator designed using FSS is proposed in [63]. MFM performed using FSS structures allows simplifying the process of frequency discrimination, since no direct connection between bulky delay lines, switched delay lines or several bulky filters is required to perform frequency identification. Because the numbers of cables and connectors are smaller, the system has less weight and fewer losses. The drawback is the need of UWB antennas.

The FSS is based on simple dipoles that have a frequency response corresponding to the characteristics of band-stop filter frequency discriminators. The proposed MFM system based on FSS has 4-bits and presents a resolution of around 300 MHz. It can identify 16 different sub-bands in the frequency range from 3.21 to 8.75 GHz. Despite its high resolution, this work is pioneering since it requires no connectors.

4.3 Digital MFM (DMFM)

The Digital MFM uses digital signal processing instead of an analog discriminator or an analog/digital system. Digital frequency discriminators frequently use signal sampling which requires fast and precise hardware [1]. Some algorithms can be implemented to directly estimate the frequency as the Fast Fourier Transform (FFT) and Chinese Remainder Theorem (CRT) [33]. An FPGA, for example, can be a hardware used to perform the calculations.

The fully digital MFM uses the Fast Fourier Transform (FFT), Discrete Fourier Transform (DFT), Chinese remainder theorem (CRT), and other algorithms to directly define the signal frequency. This method is most limited by the number of required samples in the digital device. In 2020, the authors have proposed an algorithm that splits the incoming signal into some sub-bands to solve frequency ambiguity. This method is more efficient than CRT [33] and can estimate signals with a frequency between 0 and 5 GHz with a maximum RMS error of 0.8 MHz in a short time, such as 200 ns. An ADC converter with a clock of 1800 MHz and an FPGA with a clock of 200 MHz was used to do the experimental algorithm validation.

4.4 Microwave photonics MFM (MPMFM)

MPMFM technology aims to modulate and to process the RF signals into the optical domain. The optical signals are often converted back to the electrical or sometimes digital domain and this information can be used to interpret the frequency. This can be obtained using an ACF, as aforementioned, that uniquely maps RF frequency into output signal amplitude. The most advantage of using MP in an MFM system is achieving high frequency and bandwidth and because of this, it becomes prone to future terahertz communications. This technique typically uses a March-Zehnder modulator to achieve frequency identification [34-39] with typical resolutions of up to 1.2 GHz [38]. Other designs use an electro-optical polarization modulator [40, 41], and an RF photonic Hilbert transformer [42, 64].

MFM microwave photonics technology aims to modulate and process RF signals in the optical domain. The optical signals are usually converted back to electrical or digital domains, this information is used to interpret the frequency. This can be obtained by using an ACF, as mentioned above, which uniquely maps the RF frequency to the amplitude of the output signal. The major advantage of using MP in an MFM system is to achieve high operating frequency and high bandwidth. These characteristics provide a good option for future terahertz communications. This technique typically uses a March-Zehnder modulator to achieve frequency identification [34-39] with typical resolutions up to 1.2 GHz [36]. Other designs use an electro-optical polarization modulator [40, 41], and an RF photonic Hilbert transformer [42, 64].

4.4.1 Mach-Zehnder modulator

A photonic compression receiver for measuring multiple microwave frequencies is presented in 2019 [36]. In this device, the ultra-short pulse is directly observed by an equivalent time sampling method. The frequency information of the unknown signal is directly mapped to the time intervals between compressed pulses for multiple microwave frequency measurements.

This design features an effective measurement range of 42 GHz, a multiple-frequency resolution of 1.2 GHz, measurement accuracy of 88 MHz, and a signal interception period of 27 ns. The proposed photonic compressive receiver was implemented using a Linear Chirped Optical Pulse Generator (LCOPG), an MZM, a PD, and ADC. The LCOPG generates a linearly chirped optical pulse train that is modulated by an intercepted microwave signal through an electro-optic modulator (a lithium niobate Mach-Zehnder modulator). The modulated optical pulse train is compressed by the scattering effect and converted into electrical signals by a PD. The detected electrical signal is then quantified by an ADC. The frequency components in the intercepted signal are calculated by measuring the time intervals between the pulses corresponding to the modulation term of the signal in each period.

A photonic design for microwave frequency measurement with adjustable measurement range and resolution is described in 2010 [37]. The operating principle of this design used programmable differential group delay (DGD) modules, the microwave-to-power frequency mapping technique, and an extended application of a DGD based microwave photonic filter. This principle generated a higher measurement resolution and greater simplicity compared with other schemes. This design was implemented using an BFB laser, MZM, and two measurement channels. Each channel was shaped using a programmable DGD, and a PD. The output of each channel was fed into a post-processing system to get the frequency measurement. An unknown microwave signal is modulated onto an optical carrier by using an MZM, thus, the optical output of the MZM is sent to two programmable DGD modules to introduce a different microwave power fading effect, respectively. When the microwave powers of the two channels are measured with a PD separately, a fixed relationship between the microwave power ratio and the microwave frequency is established. If the input power of a continuous-wave microwave signal is within the range of -15 to -3 dBm, the measured errors remain within ±0.04 GHz for a measurement range of 4.5–6.5 GHz. This design can operate from 0 to 20 GHz.

4.4.2 Matrix pencil assisted deconvolution

A Photonic-Assisted Scanning Receiver for Microwave Frequency Measurement based on matrix pencil assisted deconvolution for improved measurement resolution in scanning receiver systems is presented in 2019 [38]. This design adopted the deconvolution concept for scanning receiver systems for RF frequency measurement. This concept is mainly used in areas such as optical imaging and spectroscopy to break the Rayleigh criterion for point spread functions. The matrix pencil method allows an accurate recovery of frequency components by solving a generalized eigenvalue problem. This method was adopted for deconvolution due to its high robustness to noise.

The information of the input microwave signals is obtained directly from its reconstructed spectrum by means of deconvolving the system's output using the matrix pencil method, thus improving the resolution and accuracy of the scanning system. As a proof of concept, the authors performed frequency measurement of both single-tone and multiple-tone microwave signals, and the results showed that this method is effective in recovering the frequency information with high resolution and accuracy.

The proposed design was implemented using a single laser, an electro-optic modulator (EOM), an optical filter, and a low-speed photodetector and showed a significant measurement resolution reduction from 1 GHz to 0.4 GHz for two RF tones. This reduction corresponds to 30.2% of the optical filter bandwidth.

4.4.3 Photonic Microwave Filter Pair

In [39] a two-tap photonic microwave filter pair with complementary frequency responses is employed to achieve instantaneous frequency measurement. This device was introduced in 2010. The photonic microwave filter pair is implemented using a polarization modulator (PolM) and two sections of polarization maintaining fiber (PMF). The filter pair consists of a low-pass filter and a bandpass filter. The photonic microwave filter pair features a complementary nature of the frequency responses, resulting in an ACF, which is quasi-linear and monotonically decreasing over a wide frequency band, ensuring improved measurement range and accuracy. The ACF is the ratio between the two transfer functions of the filter pair. The microwave frequency measurement can be performed by simply measuring the microwave powers from the two outputs of the photonic microwave filter pair. The measurement accuracy is independent of the laser wavelength, which would eliminate the requirement for a highly wavelength-stable laser source, and hence, significantly decrease the cost and complexity of the entire system. This design presents an experimental operating range as wide as 36 GHz with a measurement accuracy better than ±0.2 GHz.

4.4.4 Electro-optical polarization modulator

Three photonics applications for microwave and millimetre wave measurements were described in 2015 [40]. These applications are used to measure instantaneous frequency (IF), angle of arrival (AOA), and Doppler frequency shift (DFS).

For Instantaneous Frequency Measurement (IFM), the proposed photonic application was implemented using a complementary optical filters pair (COFP), a diode laser (LD), and an electro-optical modulator (EOM). The LD is connected in cascade configuration with the EOM. The EOM output is divided into two branches. Each branch is implemented with an optical filter and a power meter. Finally, the outputs of each power meter feed a post-processing system to obtain the frequency of a measured signal.

The operating principle of the IFM application is described below: a microwave/millimetre wave signal is applied to an electro-optical modulator (EOM, a key device for transferring electrical signals to optical waves). The EOM is biasing at the minimum transmission point to suppress the optical carrier. Thus, the carrier-suppressed optical signal is sent to the complementary optical filters pair with two complementary transmission responses. Subsequently, the microwave frequency is measured by monitoring the filtered optical powers with two optical power meters. The proposed IFM application can operate over a range of 1 to 26GHz and has a measurement error of less than ±0.2GHz.

A simple photonic-assisted instantaneous microwave frequency measurement approach with an adjustable measurement range is described in 2020 [41]. This method features a different polarization processing is performed on the upper and the lower branches, and then the powers of the two branches are compared to obtain the amplitude comparison function (ACF), which provides the frequency-amplitude mapping. The measurement system is greatly simplified as only one PolM and a single laser source are required. In addition, this method achieves a larger ACF slope, which significantly increases the measurement resolution.

By optimizing the Direct Current (DC) bias voltage applied to the PolM and the polarization angle, this device can operate over a range of 3 - 42.8 GHz with measurement errors within ±0.1GHz.

4.4.5 Hilbert transformer

An amplitude-independent RF instantaneous frequency measurement system using the photonic Hilbert transform is presented in 2008 [42]. This system can simultaneously measure both RF frequency and power. It also uses a transversal approach to implement a Hilbert transformer which provides two orthogonal DC measurements to perform simultaneous frequency and power measurement.

Since the system features a frequency-dependent DC output, low-cost PDs were used to reduce the overall system cost. Also, by using photonic elements, a wide broad frequency detection range was achieved. The use of a Hilbert transformer made it possible to achieve the required broadband phase shift of 90°. To achieve this, the transformer used a two-tap transversal filter with an additional reference tap to make orthogonal measurements. However, since there were nulls in the transversal response, the frequency measurement range was limited between two null frequencies. This system features an operating frequency range of 1-10 GHz. A wider frequency range can be achieved through integration.

A photonic simultaneous frequency identification system of radio-frequency signals with multiple tones is described in 2013 [64]. This work also presents a mathematical model to predict the behaviour of the system. The system employs a dual-mixing technique that allows high frequency measurement without the need for any high frequency RF component or broadband photodetector. The proposed design is implemented using two signal generators, a low-frequency PD, two MZM, an erbium-doped fiber amplifier, an arrayed waveguide grating (AWG), and two low-pass filtered (LPF). The system operates over a frequency range of 0.1–40 GHz.

The proposed system works as follows: Two RF signal generators produce two single RF tones with angular frequencies of Ω_1 and Ω_2. The signals are then combined and split into two equal portions. Each portion flows through one of the IFM system arms. The RF signal in the optical path modulated three optical carriers produced by a laser array. These optical carriers are employed in a Hilbert transformer. The Hilbert transformer will work as a quadrature hybrid coupler that provides two identical signals at its outputs with a 90° phase shift difference. The Hilbert transformer was implemented using a transversal filter in which the optical carriers λ_1 and λ_2 work as transversal taps. These taps were basically samples of the impulse response of the Hilbert transformer. The carrier λ_o was used as a reference to provide a 0° phase shift against which the 90° phase shift was compared. A 3 dB optical coupler combined the carriers λ_1 and λ_2. This combined signal together with λ_1 was modulated in push-pull mode using an MZM to realize the desired combination. The modulated signal was fed input to port1 of an optical circulator. Port 2 of the circulator was connected to a cascaded grating. The cascaded grating reflected each wavelength with different but uniformly incremented delays (τ_0).

This delay was required to implement the transversal filter. The scattered signal exited through port3 and entered MZM2 fed with the original RF signal. The output of MZM2 was then amplified by an erbium-doped fiber amplifier (EDFA) and fed into an AWG that separated all wavelengths. The carrier λ_o remained separated and was used as the reference. The carriers λ_1 and λ_2 were again combined using a 3 dB coupler to make the two-tap transversal filter. Both signals were detected using low-frequency PDs (PD1 and PD2), and low-pass filtered. The resulting signals were measured with digital voltmeters.

4.4.6 Stimulated Brillouin scattering process and nonlinear fitting

In 2019, the stimulated Brillouin scattering process and nonlinear fitting are presented to demonstrate a multiple microwave frequency measurement [44]. This proposed device used a simple and feasible multiple MFM scheme utilizing a two-stage stimulated Brillouin scattering (SBS) and a nonlinear fitting. SBS is one of the most common nonlinear effects in single-mode fiber and has been extensively investigated.

By sweeping a reference frequency during the stimulated Brillouin scattering process, the frequency information of the microwave signal to be measured is detected by the created mapping between the total output power of the system and the reference frequency. The nonlinear adjustment is used to mitigate the line width limitation of the Brillouin gain spectrum and the measurement resolution is significantly improved.

The unknown multiple frequencies to be discriminated and the reference frequency signal are modulated in the carrier wave respectively, which are involved in the nonlinear SBS interaction. The two-stage SBS structure helps to achieve measurements with low error.

By monitoring the changes of the system output optical power along with the swept reference frequency, the multiple unknown microwave frequencies can be evaluated without ACF. Since the two-stage structure to improve the frequency resolution is insufficient, it is necessary to apply a nonlinear fitting method is applied to the measured data processing. The frequency resolution of the system is mainly reduced by nonlinear adjustment. The minimum resolvable frequency difference of 18 MHz is realized when multiple frequencies are measured. The measurement error is less than 5 MHz with a 21.42 GHz wideband. The proposed device was implemented using an LD, two Intensity modulators, single-mode-fiber (SMF), two single-mode fibers, and two circulators.

4.4.7 Electro-optical modulator

In [42], 2008, a simple photonic-assisted instantaneous microwave frequency measurement approach with an adjustable measurement range is described. Different polarization processing is performed on the upper and the lower branches of the device, and then the power of the two branches are compared to obtain the ACF, which provides the frequency-amplitude mapping. The measurement system is significantly simplified since only one PolM and one single laser source are required.

4.4.8 Polarization multiplexing modulator

A reconfigurable instantaneous frequency measurement system based on a Dual-polarization Dual-drive Mach-Zehnder modulator (DPol-DMZM) was reported in 2019 [65]. By simply adjusting the DC biases on both arms of the DPol-DMZM, the upper and lower bounds of the IFM measurement range can be independently adjusted, defining the bandwidth. The proposed IFM is easy to be reconfigured with an adjustable measurement range and resolution. This design shows that the lower frequency bound is as low as 2 GHz, and the upper frequency bound is up to 23 GHz. The resolution of ±0.2 GHz is reported for three frequency measurement bandwidths of 5, 6.5, and 8 GHz.

4.4.9 Programmable DGD modules

A photonic design for microwave frequency measurement with adjustable bandwidth and resolution was proposed in 2019 [36]. After an unknown microwave signal is modulated onto an optical carrier by an MZM, the optical output of the MZM is sent to two programmable DGD modules to introduce a different microwave power fading effect, respectively. The frequency measurement range and resolution can be tuned by electrically varying DGD values.

4.4.10 Deep neural MP

In [66], a reconfigurable instantaneous frequency measurement system based on a DPol-DMZM is reported. By simply adjusting the DC biases on both arms of the DPol-DMZM, the upper and lower bounds of the IFM measurement range can be independently adjusted, defining the bandwidth. The proposed IFM is easy to reconfigure with an adjustable measurement range and resolution. This design shows the lower frequency bound to be as low as 2 GHz, and the upper frequency bound is up to 23 GHz. The resolution of ±0.2 GHz is reported for three frequency measurement bandwidths of 5, 6.5, and 8 GHz.

5. Discussion on MFM challenges

In Electronic Warfare (EW) receiver design, the determination of the optimum bandwidth and resolution, including the limits of receiving two simultaneous signals with no ambiguity are the main challenges. Table 1 provides a comparison between commonly used EW receivers. IFM receivers have several technical advantages over other receivers, i.e., IFM receivers have excellent instantaneous frequency bandwidth and high resolution when compared to other receivers, e.g., resolution of 1 MHz considering a 0.1 us pulse, and an instantaneous input bandwidth of around 16 GHz (e.g. from 2 to 18 GHz). Crystal and superheterodyne receivers perform well in either bandwidth or resolution, i.e., crystal receivers have an excellent bandwidth, but a poor resolution [81-85]. While the superheterodyne receiver features poor bandwidth but excellent resolution. Superheterodyne receivers perform better than IFM receivers when it comes to sensitivity and dynamic range, where IFM receivers perform fair to good. In conclusion, IFM receivers have acceptable performance in terms of bandwidth, resolution, dynamic range, and sensitivity.

Channelled [2, 5, 76, 84-88] and compressive [2, 5, 92-98] receivers can handle simultaneous signals. The sensitivity and dynamic range of channelled and compressed receivers are high. The bandwidth of channelled receivers depends on the number of parallel channels used; frequency resolution depends on filter bandwidth. Compressive receivers have a moderately wide bandwidth. Optical receivers [2, 5, 89-93], implemented using the Bragg cell [89-93], present high sensitivity, wide bandwidth, and simultaneous signal processing, with poor dynamic range and fair sensitivity.

Microwave frequency measurement receivers have evolved since the first analog receiver designs, implemented with cathode-ray tubes, magic tee waveguides, delay lines, coaxial rings [2-4]. These designs occupied a volume of approximately 147 cm^3 with a weight between 15 and 50 kg, whereas some heavy designs had a steel structure. Recent analog/digital and digital frequency measurement designs occupy areas between 16 and 830 cm3.

Reconfigurable frequency measurement receivers [12,13,15] aim to drastically reduce receiver size by using embedded switching elements, allowing the use of less electronic components, resulting in lower power consumption, with a serial non-instantaneous output. Newly implemented microwave frequency measurement using frequency selective surfaces [63] can be performed with no connectors using metal and dielectric periodic patterns.

IFM receivers can be used as Radar Warning Receivers (RWRs), Radar Homing and Warning Receivers (RHWRs), and Electronic Countermeasure (ECM) receivers, because of their performance characteristics shown in Table 1. These features are wide input frequency range, frequency resolution, sensitivity, and small size. They can also be used in conjunction with other receivers and as electronic support measure (ESM) receivers and electronic intelligence (ELINT) receivers.

However, IFM receivers have presented a major disadvantage since their origin. This disadvantage is the inability of receiving and processing two different signals simultaneously. When an IFM receives two or more signals at the same time, the IFM is not able to process them, so the IFM generates or produces erroneous information.

IFM receivers use the nonlinearity of crystal detectors to generate the autocorrelation of the input signal. Correlators (or frequency discriminators) are the core of an IFM receiver.

A solution to multiple signals can theoretically be obtained from autocorrelations with many lags. Therefore, the IFM receiver should therefore be able to handle simultaneous signals. There have been numerous attempts to improve its ability to process simultaneous signals, but with limited success [71]-[74].

A reason for the limited success of IFM receivers for measurement simultaneous signals is that they use crystal detectors in the correlator. Since the detectors have a dynamic range of about 15 dB, a limiting amplifier is placed in front of the detector in order to maximize the single frequency dynamic range of the receiver.

Basically, a limiting amplifier (LA) is a nonlinear device. With only one signal in the input of the LA, its nonlinear effect can be neglected, and the strongest output will be the true signal. Thus, the receiver measures this signal with high accuracy, but if there are multiple signals at the input of the LA, the nonlinear effect cannot be neglected. In consequence, the output of the correlator is no longer the desired autocorrelation.

A solution to solve the problem of measurement of simultaneous signals is proposed in [70]. This solution is based on Prony's method. However, no evidence of the use of the method in current commercial IFM receivers was found. Thus, this indicates that the implementation of Prony’s method is the difficult part.

In [75] is proposed a method to simultaneous signal detection using the intermodulation effect. This method uses a mixer to detect the existence of intermodulation frequencies.

If there is only one input signal, the output from the mixer will be a dc voltage. If more than one signal is presented at the input of the mixer, intermodulation frequencies will be generated at the output of the mixer. It also uses a low-pass filter to block the input signals but it allows the passage of the intermodulation frequencies. Finally, a detector is used to convert these frequencies to corresponding dc voltage. This voltage is compared against a fixed threshold.

Another way to solve the problem of simultaneous signal detection is to use the concept of a channelized receiver in the design of IFM receivers [68, 76-78]. In order to resolve the major disadvantage of this type of receiver, which is in the parameter encoders, this concept needs to be carefully examined.

In [79] is presented a theoretical analysis which is based on McCormick and Lansford to measure the frequency of two simultaneous signals. The analysis provides the basic equations to measure the frequencies of two input signals and is based on continuous functions in the time domain.

Nowadays, several research groups are searching for suitable solutions to enable IFM receivers to measure simultaneous signals with high accuracy and reduced error [5, 69-74]. Although the receivers are incapable of measuring simultaneous signals. They have important features for measuring and identifying the frequency of an individual signal. This has allowed a natural evolution in the development and design of IFM receivers to improve their functional performance (resolution, bandwidth, etc.), as well as to reduce weight and size. This evolution has been achieved by using the new technologies of the time and applying mathematical and design concepts from other areas of technological development [1-67].

Table 2 shows a comparison among various MFM receiver designs [1-67]. In this work, a new classification of MFM circuits is proposed. The proposed classification in fig. 10, is based on the technology used to implement the receivers and is defined in four categories such as analog (AMFM), analog/digital (ADMFM), digital (DMDM), and photonic (MP MFM).

AMFM receivers have used different technologies for their implementation such as cathode ray tubes, coaxial cable rings, waveguides, etc. [1, 2, 7, 8, 51, 52, 57-59]. As a result, these designs had a resolution between 100 and 400 MHz, with an instantaneous response time. In addition, these have worked in the range from MHz to 40GHz. The GHz frequencies were achieved using waveguides.

The first MFM devices were designed using waveguide and coaxial transmission lines that were the rule of thumb [2]. They were completely analog devices and used detectors or oscilloscopes to see the parameter correlated to the frequency. They are in general low bandwidth, low resolution and normally occupy a large area. More details about some of these devices also can be found in [2]. Even being used in the first MFM systems, the analog mapping technique is still currently used in the MP MFM techniques.

ADMFM receivers have used delay lines, Frequency Selective Surface (FSS), filters, etc. for its implementations [1, 2, 9-18, 20-27, 61,62]. The application of these technologies has provided designs that operate in the I, G, P, S, C, and X bands with a resolution ranging from 2.5 to 940 MHz. As well as presenting different numbers of output bits ranging from 1 up to 15.

The ADMFM devices are an evolution of the analog MFM systems because they provide a digital output that can be post-processed, providing a higher accuracy frequency identification. Other ADMFM advantages are: low power consumption, low cost, good sensitivity and good dynamic range. Because of these reasons, they are most popular in the industry [62].

They need an analog frequency discriminators as delay lines, reconfigurable delay lines, filters, or FSS to define the region in the spectrum where the frequency signal is most likely to be; an ADC/Arduino® in the conversion stage, and, some of them use FPGA to implement algorithms to estimate the frequency with fewer errors. Recent papers using algorithms have achieved an accuracy similar to the commercial ADMFM devices that is around 1 MHz [61].

In this category of receivers, the innovative design of reconfigurable IFM receivers is presented [1,12,13]. These receivers can generate n-bits of output for frequency measurement, using only a reconfigurable discriminator that was implemented with microstrip transmission lines and PIN diodes. These designs generate n-bit receivers that operate in the L and S frequency bands and with a resolution defined as

$$f_R = {}^{1}/_{2^{n+1}\Delta\tau max}$$

Where $\Delta\tau$max is the maximum gradient of the system.

In addition, these designs use the same amount of electronics as a single bit output receiver for frequency identification. This results in lower power consumption, lower weight, smaller size, and low cost. They need a processing time of a few ns (~10 ns [1,12,13] if PIN diodes are used) due to the use of switches and because of this the frequency identification is not instantaneous.

A design based on the concept of reconfiguration, planar technology, and fractal structures is presented in [15]. This design has 3 output bits, and a resolution of 225 MHz. It operates in L and S bands.

The Frequency Selective Surface (FSS) concept is used to design an IFM receiver [63]. This design operates in the S, C and X frequency bands.

Also in this category, the use of the concept of digitalization of the output signals of IFM receivers is introduced, allowing the use of digital analog converters, microprocessors, digital signal processors (DSP) and FGPA for the interpretation of the resulting signal [24, 61,62]. The most recent papers using filters discriminators and post-processing have presented devices with high accuracy (1.7 MHz [61]) and dynamic range (70 dBm [62]) similar to the commercial versions.

The ADMFM system is power dependent. Some algorithms can be used to mitigate this problem [62]. The electromagnetic noise and interference are also another drawback [66]. Additionally, the operating band and bandwidth are limited, the commercial ones have a bandwidth around 20 GHz, but most of the MFM systems found at the start-of-the-art have a bandwidth between 1-4 GHz .

In recent decades, with the development of high-speed ADC and the FPGA, the possibility of doing the instantaneous measurement without using analog discriminators is increasing but is still limited by the devices' clocks. The DMFM system identifies frequencies just until 5 GHz with a good resolution of 0.8 MHz [65]. The DMFM can provide a system with reconfigurable frequency and bandwidth and it also can estimate several different signal frequencies at the same time.

In this category of digital IFM receivers, a design is presented that is implemented with FPGA and based on Chines Remainder Theorem [33].

Finally, in the category of IFM receivers based on Photonics technology - MPMFM, various mathematical concepts and the Mach-Zehnder modulator (in most cases) are used to determine the frequency of a measured signal [34-38, 40-44, 65, 66]. The MPMFM have the advantages of broad frequency measurement range and bandwidth (1- 52 GHz), low loss, lightweight, and immunity to electromagnetic interference compared to the planar techniques (up to 20 GHz) [65].

Despite the high bandwidth, this technique presented in the beginning low resolution and high frequency error of hundred megahertz (100 to 1200 MHz) [67]. Some advances on there were proposed using a deep neural network-assisted [66] where the measurement of high frequency signals from 43 to 52 GHz is experimentally demonstrated in 200 MHz steps achieving average errors of about 3.2MHz.

In [36], despite the error of 88 MHz, the authors have proposed an MPMFM system to identify the multiple-frequency signal in a 42 GHz range with a resolution of 1.2 GHz. These designs also introduce the concept of reconfigurable receivers with the possibility of operating in two frequency intervals for the case of [34,], and for the case of [37] it presents six measurement intervals. Both have an average resolution of ± 140 MHz.

Due to the band limitation of the electronic MFM, the MPMFM has proven to be the most prone technique to achieve high frequency and bandwidth, to estimate complex and multiple frequency signals for high frequencies that can attend the requirements of 5G technology. In addition, it is possible to fabricate these devices using Silicon-Based Integrated technologies which provide the reduction of the size, cost, weight, and power consumption; and possibilities the integration with high-speed silicon electronics [80].

6. Conclusions

This paper provides an overview of microwave frequency measurement, from initial designs that involve long coaxial delay lines and operate up to X band, resulting in bulky and heavy designs, with high resolutions of about 1 MHz with analog/digital implementations. Low-cost implementations using microwave laminates and planar circuits are reviewed, some as fixed designs where a frequency discriminator per bit is used or reconfigurable versions, suitable for lightweight implementations, with potential use in class I unmanned aerial vehicles.

Frequency selective surfaces have been recently used for frequency measurement and are suitable for implementations operating at millimetre waves or THz. Frequency measurement can be performed with no need for lengthy delay lines or bulky filters, instead a sheet or substrate with a band-stop filter response can be used with no need for connectors.

Microwave photonic based devices have been used for fixed and reconfigurable frequency measurement at frequencies up to 42 GHz and produced at a higher cost and larger dimensions compared to compact low-cost designs, while being free of electromagnetic interference.

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Table 1. A Comparison of performance of EW receivers.

Implementation	Instantaneous frequency bandwidth	Frequency resolution	Dynamic Range	Sensitivity	Simultaneous signal handling capability	References
IFM	Excellent	Good	Fair to Good	Fair to Good	Poor	[2,5,1-67]
Crystal	Excellent	Poor	Fair	Poor to Good	Poor	[2,5,81-85]
Channel	Good	Good	Good	Good	Good	[2, 5, 76,84-88]
Optical	Good	Good	Fair	Fair to Good	Good	[2,5, 89-93]
Compressive	Good	Good	Good	Good	Good	[2, 5,92-98]
Superhet	Poor	Excellent	Excellent	Excellent	Poor	[2,5,84-85]

Table 2. MFM techniques comparison.

Frequency Band (GHz)	Type of system	No. Discriminators	Response Time	No. Bits	Resolution (MHz / °/%)	Size (mm)	Technology/ Implementation	Ref./ Year
Analog (early stages) AMFM								
0.950-1.050	Fixed	1	Instantaneous	---	100Hz	Not informed	8 RC circuit, a delay network, a phase shifter and a cathode ray oscilloscope.	[52] 1948

0.15-11.5	Fixed	1	Instantaneous	---	±5°	Not informed	Solid state/ Coaxial ring, delay lines and detector diodes	[7,8] 1958
0.050-0.25	Fixed	1	Instantaneous	---	13%	Not informed	A power split, shorted stubs, and a video data processing stage.	[59] 1962
≤40GHz	Fixed	1	Instantaneous	---	400MHz	Not informed	A magic tee waveguide, a circulator, two line-matched detectors, one line length, and two shorts	[54] 1970
≤35GHz	Fixed	1	Instantaneous	---	400MHz	Not informed	A magic tee waveguide, a circulator, two line-matched detectors, one line length, and two shorts	[56] 1980
Analog/Digital ADMFM								
Based on Delay Line								
2-4	Fixed	1	Instantaneous	1	Not informed	Not informed	Solid state / delay line	[9] 1972
-	Fixed	6	Instantaneous	1	2.5	40x50	Solid state /Bipolar LSI technology	[10] 1979
9.5-10.5	Fixed	4	Instantaneous	4	248.4	40x40	Coplanar $Y_1Ba_2Cu_30_{7-\delta}$ delay lines on $LaAlO_3$ substrates	[19] 1995
5.12-5.82	Fixed	1	Instantaneous	1	Not informed	~ 139.45x 14.53	Based on coplanar interdigital delay lines	[6] 1996
0.150 - 0.550	Fixed	8	Instantaneous	8	2	76.2x102x 19	Based on delay lines (microstrip)	[11] 1998
5-6	Fixed	4	Instantaneous	4	243.90	~50x53.25	Based on coplanar strips (CPS) delay-line	[14] 2009
2-4	Fixed	7	Instantaneous	7	1	~ 500x500	Solid state/ Based on delay lines (strip line)	[2] 2012
1-4	Reconfigurable	1	delayed (10ns)	2	600-940	45x65	Solid state /Based on delay lines (microstip)	[1,12] 2017,2014
4.66-6.38	Fixed	3	Instantaneous	3	215	~90x90	Based on Hilbert fractal geometry.	[16] 2015
1-4	Reconfigurable	1	Delayed (10ns)	4	187.5	102x96	Solid state /Based on delay lines (microstip)	[1,13] 2017, 2016
4-6	Fixed	4	Instantaneous	4	125	81.5x90.1	Based on delay line	[18] 2016
2.7-4.5	Reconfigurable	1	delayed	3	225	53x39	Solid state /Based on Fractal delay line	[15] 2019

4.66–6.38	Fixed	4	Instantaneous	4	107.5	~90x120	Based on Hilbert fractal geometry.	[17] 2017
Based on Filters								
2-4	Fixed	15	Instantaneous	15	12.5 MHz	210x150	Solid state /Based on frequency-shifted filters/FPGA	[24] 2008
2-4	Fixed	5	Instantaneous	5	62.5 MHz	~200x150	Open-loop resonator based bandstop filters	[20] 2009
1.5-4.66	Fixed	4	Instantaneous	4	40-900 MHz	199x113	Open-loop resonator based bandstop filters	[21] 2014
2-4	Fixed	5	Instantaneous	5	62.5 MHz	Not informed	Bases on quarter-wavelength band-stop filters	[27] 2014
2-4	Fixed	4	Instantaneous	4	15 MHz	~190x50	Based on band-pass filter.	[22] 2017
2 -4	Fixed	4	Instantaneous	4	11 MHz	~60x150	Based on band-pass filter.	[26] 2017
2-4	Fixed	7	Instantaneous	7	15.6 MHz	~557x150	Based on microstrip band-stop spiral filters	[23] 2018
2-4	Fixed	7	Instantaneous	7	15.6 MHz	220x180	Solid state /Microstrip band stop filters	[25] 2018
2-4	Fixed	6	Instantaneous	6	31.25 MHz	~120x50	Microstrip band-stop filters	[28] 2018
2-4	Fixed	8	Instantaneous	8	1.7 MHz	Not informed	Microstrip filters/ Minimum Mean Square Error (MMSE)/ FPGA/ 20 dBm Dynamic range/ 156 K pulse/s	[61] 2020
2-4	Fixed	15	Instantaneous	15	11 MHz	Not informed	Microstrip filters/ Minimum Mean Square Error (MMSE)/ FPGA/70 dBm Dynamic range/ 8.3 M pulse/s	[62] 2021
Based on Frequency Selective Surfaces								
3.21-8.75	Fixed	4	Instantaneous	4	300Mhz	210 x 210	Frequency selective surfaces (FSS)	[63] 2018
Digital IFM DMFM								
0-5	Fixed	1	Instantaneous	1	0.8 MHz	Not informed	Based on Chinese remainder Theorem (CRT)/FPGA	[33] 2020
Based on Microwave photonics MPMFM								
3-42.8	Fixed	1	Instantaneous	--	100	Not informed	Based on an electro-optical polarization modulator	[42] 2008

1-18	Fixed	--	Instantaneous	--	200	Not informed	Microwave photonic /Dual parallel Mach-Zehnder modulator	[35] 2009
1-12, 2-13	Reconfigurable	1	Instantaneous	--	±100 ±250	Not informed	Microwave photonic /Dual parallel Mach-Zehnder modulator	[34] 2012
Fixed measurement band: 2-7, 10-15 18-23. Lower measurement band: 10-15, 10-16.5, 10-18.	Reconfigurable	1	Instantaneous	--	±200 ±100 ±120 ±100 ±120 ±200	Not informed	Microwave photonic /Mach-Zehnder modulator and two programmable differential group delay module (DGD).	[37] 2010
1-20	Fixed	1	Instantaneous	--	400	Not informed	Microwave photonic /Based on matrix pencil assisted deconvolution	[39] 2010
0.1-40	Fixed	1	Instantaneous	--	Not informed	Not informed	Based on polarization- [illegible]	[64] 2013
1-36	Fixed	1	Instantaneous	--	±200	Not informed	Photonic Microwave /Filter Pair	[40] 2015
4.5-6.5	Fixed	1	Instantaneous	--	±40	Not informed	Microwave photonic /Dual parallel Mach-Zehnder modulator	[36] 2019
0.11-21.42	Fixed	1	Instantaneous	--	18	Not informed	Based on Stimulated Brillouin Scattering and Nonlinear Fitting	[44] 2019
0.6 - 42	Fixed	1	Instantaneous	--	1200	Not informed	Microwave photonic /Mach-Zehnder modulator	[38] 2019
2-23 with five range **2-7, 10- 5, 18-23 10-16.5 10-18**	Reconfigurable	1	Instantaneous	--	±0.2 ±0.1 ±0.12 ±0.12 ±0.2	Not informed	Based on dual-polarization dual drive Mach-Zehnder modulator (DPol-DMZM))	[65] 2019
1-10	Fixed	1	Instantaneous	--	Not informed	Not informed	An RF photonic Hilbert transformer	[41] 2020
43-52	Reconfigurable	1	Instantaneous	--	3.2 MHz	Not informed	Deep neural network-assisted/ Photonic scanning receiver	[66] 2020

Fig. 1

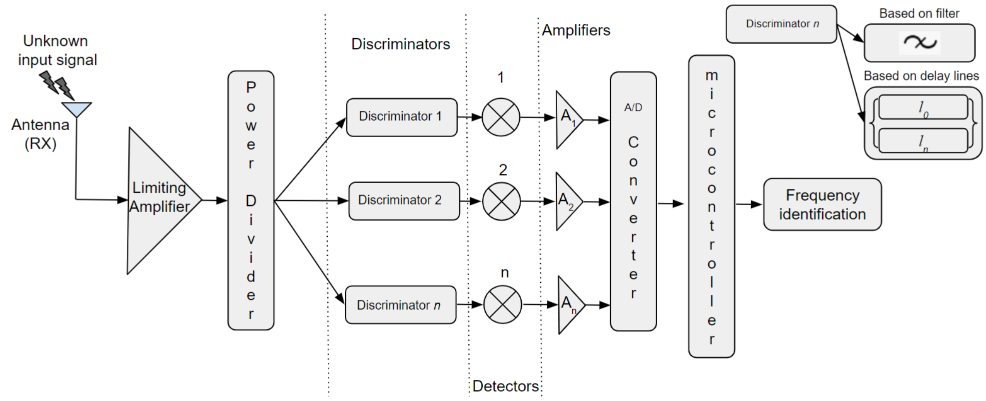


Fig. 2

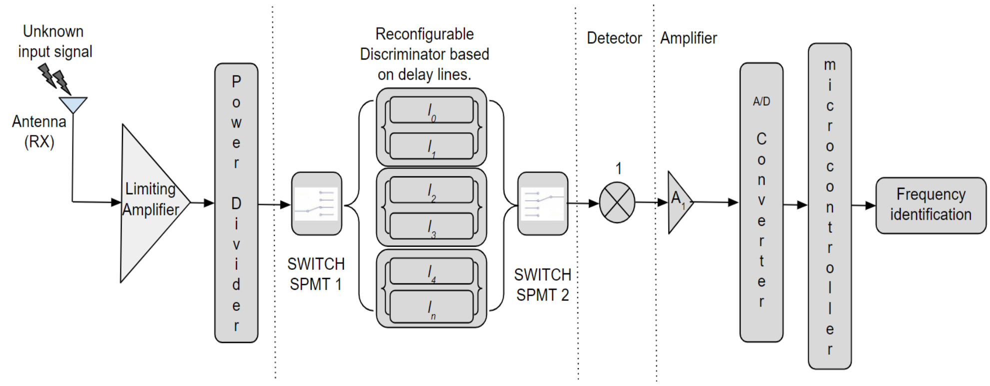


Fig. 3

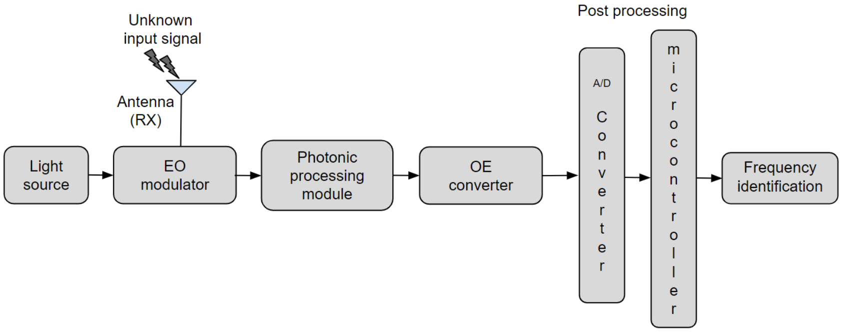
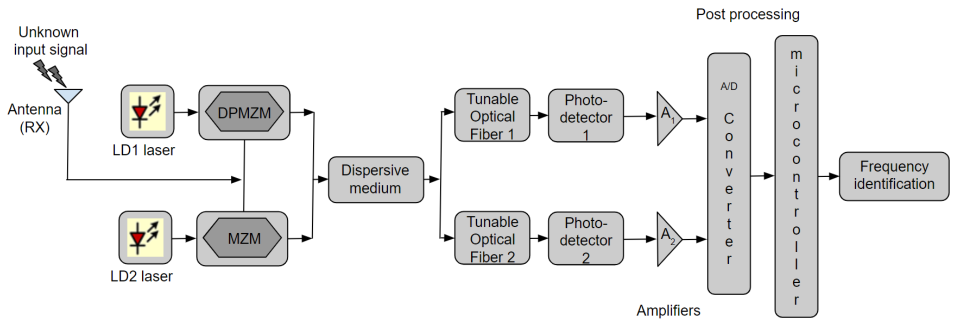


Fig. 4



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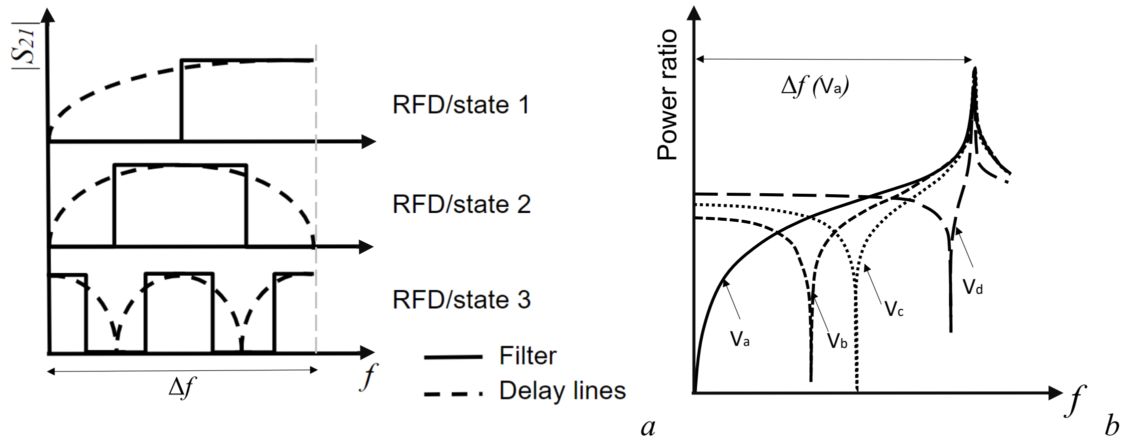


Fig. 6

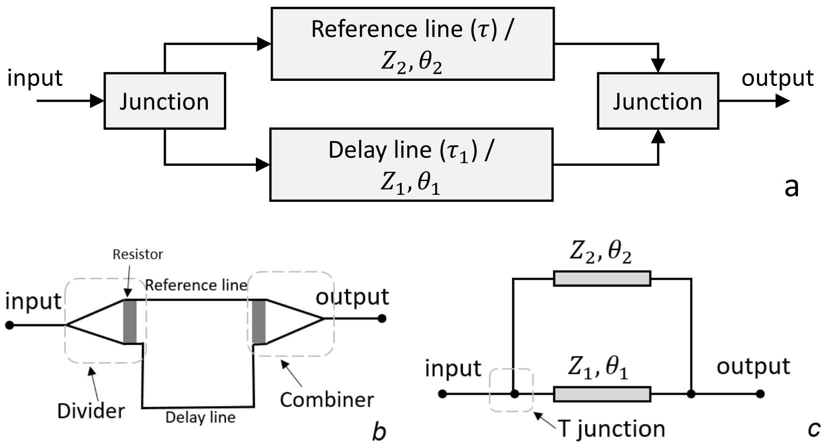


Fig. 7

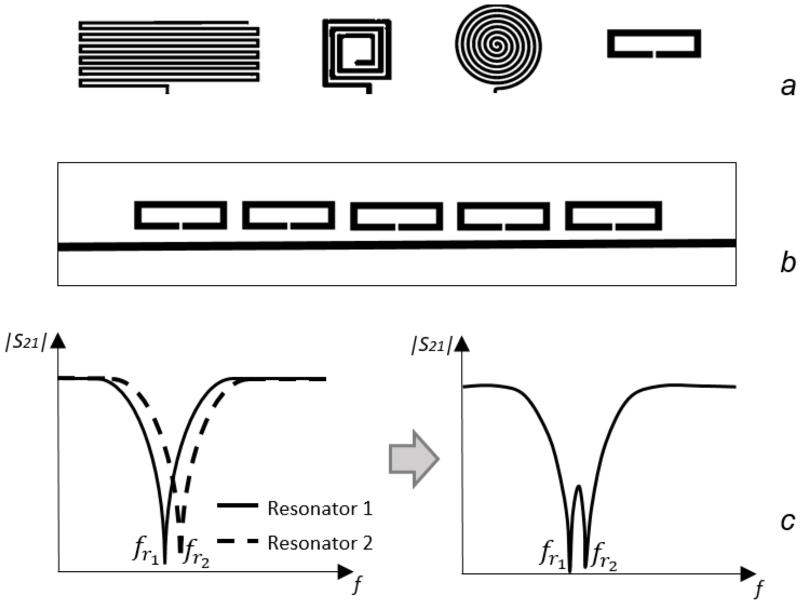


Fig. 8

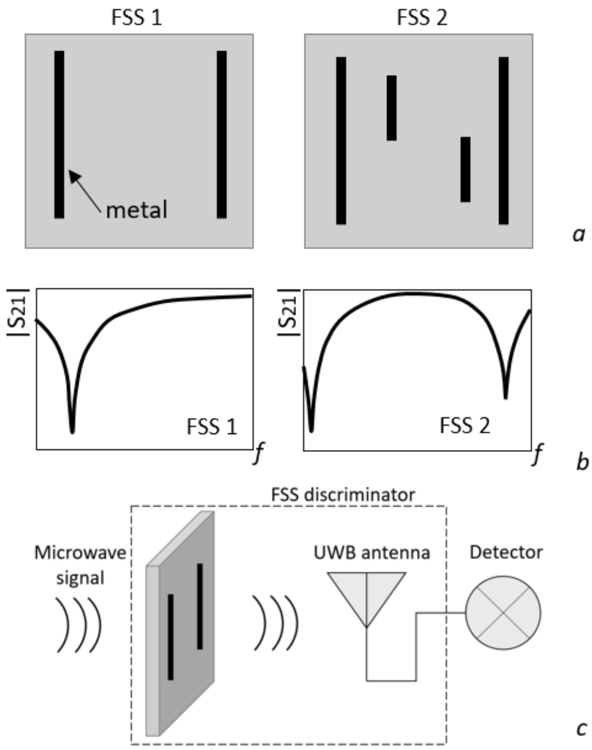


Fig. 9

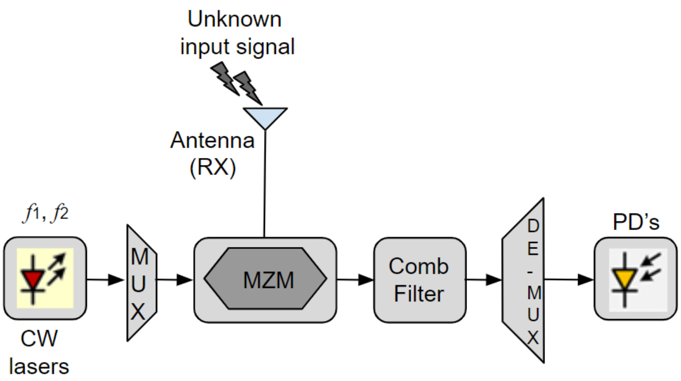
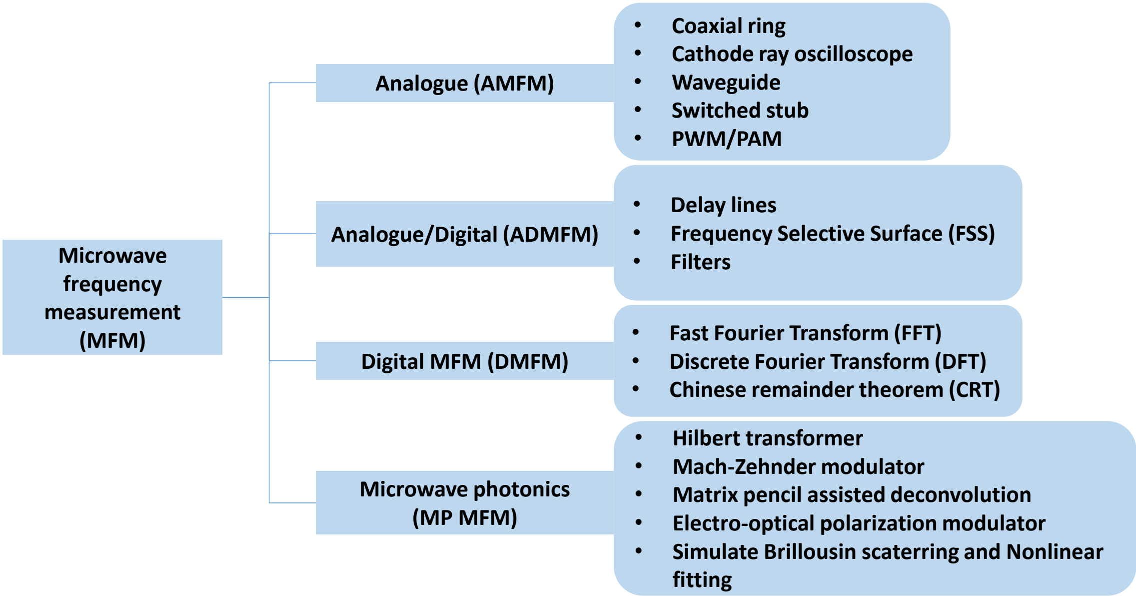


Fig. 10



Microwave frequency measurement (MFM)
Analogue (AMFM)
Coaxial ring
Cathode ray oscilloscope
Waveguide
Switched stub
PWM/PAM
Analogue/Digital (ADMFM)
Delay lines
Frequency Selective Surface (FSS)
Filters
Digital MFM (DMFM)
Fast Fourier Transform (FFT)
Discrete Fourier Transform (DFT)
Chinese remainder theorem (CRT)
Microwave photonics (MP MFM)
Hilbert transformer
Mach-Zehnder modulator
Matrix pencil assisted deconvolution
Electro-optical polarization modulator
Simulate Brillousin scaterring and Nonlinear fitting

Fig. 10 MFM based on delay lines or filters.

Fig. 11 MFM based on reconfigurable delay lines.

Fig. 12 Microwave photonic MFM.

Fig. 13 Reconfigurable microwave photonic MFM [32].

Fig. 14 Typical frequency response: (a) For delay line or filter MFM and (b) microwave photonics MFM - ACF curve [32].

Fig. 15 Signal-interference circuit diagram based on delay lines. (a) General diagram, (b) With divider/combiner, (c) With T junction.

Fig. 16 Discriminator based on a filter. (a) Resonator geometry examples: meander line, square and circular spiral loop and rectangular loop, (b) Microstrip filter with rectangular loop resonators, (c) Frequency response with two resonators.

Fig. 17 Discriminator based on FSS. (a) Two FSS examples, (b) FSS frequency response, (c) FSS discriminator. [31]

Fig. 9 MP discriminator using a comb filter.

Fig. 10 Proposed classification of microwave Frequency measurement Circuits.