LETTER

Ultra-wideband generator of coherent multicarriers for multipactor sensor system

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Abstract Multicarrier signals are used in many radio frequency and microwave systems. A typical example is the wideband communication satellites. However, it is rare to require the carriers in such multicarrier systems to be coherent due to the fact that their frequencies are different. An exception is the testing system for Multipactor Sensor System (MSS). Compared with existing methods that rely on the heavy use of expensive microwave instruments, in this work, we demonstrate an ultra-wideband coherent multicarrier generator (UCMG) with commercial chips and economic devices, which works from UHF to Ku band. MSS experimental results verified the novelty and effectiveness of the proposed approach. The implemented UCMG would make it affordable for a regular microwave laboratory to conduct quantitative experimental researches on wideband multicarrier multipactors. It can also be widely used in other RF systems such as massive MIMO and large-scale phase array systems.

Keywords: coherent multicarrier generator, multipactors sensor system, FPLLs

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

For an electrical system, the word “coherence” implies that the phase differences between two (or more) sinusoidal signals remain constant. Conventionally, this coherence is defined for signals with the same frequency. Therefore, it is quite rare to require the carriers in a multicarrier system to be coherent, in which case their frequencies are different. For sinusoidal signals with different frequencies, “coherence” implies that the initial phases of such signals are not only constant, but also predefined. A typical example of a system requiring such an unconventional coherence is the wideband multicarrier Multipactors Sensor System (MSS).

In 1934 [1] the multipactor phenomenon was observed in vacuum high-power microwave devices. After that, theory model and production of multipactor have acquired many results to throw light on the multipactor phenomenon [2, 3, 4, 5, 6, 7, 8, 9]. Numerical and simulation method are introduced to find out multipactor effects in high-power microwave devices [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20]. These conclusions show that it occurs when electrons ac-

celerated by intense electric fields are self-sustained via an avalanche due to the secondary electron emission. In a multipactor, secondary electrons can be exponentially increased. The resultant convection current can severely interfere with useful signals, or even damage the device [3]. Therefore, the prevention of multipactor discharges is of vital importance for high-power microwave systems in space applications. With the rapid development of multicarrier high-power systems such as wideband communication satellites, researches on MSS become more and more important [6, 7, 21, 22]. In order to investigate the occurrence threshold of multicarrier multipactor, ultra-wideband generation of coherent multicarrier signals is indispensable. Unfortunately, only a few works were involved with experimental setups of MSS for the multicarrier multipactor thresholds measurement [7, 21, 22, 23, 24, 25] until recently. Apart from a narrow-band UHF system, the only wideband systems are the 12-channel Ku-band MSS established with the massive use of expensive commercial instruments [7, 23, 25] which is hard to afford for regular laboratories.

In this work, we demonstrate the experimental implementation of an ultra-wideband coherent multicarrier generator (UCMG) based on a state-of-the-art Fractional-N phase-locked loops technique. Compared with existing methods that rely on the heavy use of expensive microwave instruments, proposed 12-channel UCMG is implemented with commercial chips and economic devices. It works with an ultra-wide bandwidth from UHF to Ku band. Experimental results verified the novelty and effectiveness of the proposed approach. The implemented UCMG would make it affordable for a regular microwave laboratory to setup an experimental MSS and conduct quantitative researches on wideband multicarrier multipactors. It can also be widely used in various systems such as massive MIMO and large-scale phase array systems.

The paper is arranged as follow. In section 2, the implementation of a MSS and the generation of coherent multicarrier from proposed UCMG is described. In section 3, the principle and implementation of the UCMG is clearly introduced. In section 4, the in-system calibration of UCMG and its usage in the MSS is demonstrated. In section 5, we draw a brief conclusion of this paper.

2. System description

In Figure 1, a block diagram of a conventional MSS is introduced, which consists of three subsystems, i.e., a high-power

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Fig. 1 Experimental setup of conventional MSS

Fig. 2 Block diagram of the high-power UCMG

UCMG, a reflection monitor, and a vacuum chamber. An additional harmonics monitor is needed in order to observe the nonlinear response of the device under test (DUT) producing in the MSS [26]. At first, the UCMG will generate a coherent multicarrier signal to excite the DUTs. As the power of the multicarrier signal increasing, a sudden change of the multicarrier signal reflection will be observed from the reflection monitor. So, the amplitude of input multicarrier power that cause this change can be regarded as the multipactor threshold of the DUT.

The block diagram of proposed UCMG is shown in Figure 2. It includes 12-channel vector RF signal generators, the power management module and an output multiplexor (OMUX) that is used to combine multiple carriers into a coherent multicarrier signal.

In mathematics, the multicarrier signal $S(t)$ can be written as:

$$S(t) = \sum_{i=1}^N A_i \cdot \cos \left(2\pi \left(f_1 + \sum_{j=1}^{i-1} \Delta f_j \right) \cdot t + \frac{\pi}{180} \cdot \varphi_i \right) \quad (1)$$

where N is the number of carriers, A_i and φ_i are the amplitude and phase of the i -th carrier, respectively. f_1 is the frequency of the first carrier, and Δf_j means the frequency spacing between two close carriers. $S(t)$ is periodic, whose periodicity is the least common multiple of the periods of all carriers.

In practical systems, A_i and Δf_j are normally constants, thus the waveform of $S(t)$ is only determined by φ_i . So, in the “in-phase” case where φ_i is a constant [7], equation (1) can be re-written as a sinc function:

$$S(t) = A_0 \frac{\sin(N\pi\Delta f t)}{\sin(\pi\Delta f t)} \cdot \cos \left[2\pi \left(f_1 + \frac{N-1}{2} \Delta f \right) \cdot t \right] \quad (2)$$

And in the “triangular-phase” case where the initial phases of the N carriers have a discrete linear relationship [7], the waveform of $S(t)$ can be described as:

$$S(t) = A_0 \sum_{i=1}^{\frac{N-1}{2}} \cos \left\{ 2\pi [f_1 + (i-1)] \cdot t \right.$$

Fig. 3 Waveform of 6-carrier signal. (a) “in-phase” 6-carrier signal. (b) “triangle-phase” 6-carrier signal.

$$+ \frac{\pi}{180} \cdot \frac{4k(N-2)(i-1)}{(N-1)^2} \left\{ + A_0 \sum_{i=\frac{N+1}{2}}^N \cos \left\{ 2\pi [f_1 + (j-1) \cdot \Delta f] \cdot t + \frac{\pi}{180} \cdot \frac{4k(N-2)(N-i)}{(N-1)^2} \right\} \right\} \quad (3)$$

For demonstration, Figure 3 shows the waveform of 2 six-carrier signal as (2) and (3) described, where $f_1 = 800$ MHz and $\Delta f_j = 1.25$ MHz. Figure 3 indicates that with the same f_1 and Δf_j , different phase combinations can result in very different waveforms. Also, the multipactor thresholds of the same DUT can be significantly different.

That is the reason why the UCMG used in an MSS should be able to set the phases, frequencies and amplitudes of each carriers independently. However, because of the strict demand for the independence of each carrier’s initial phase, amplitude and frequency, the generation of exciting signal of a MSS is of great challenge for regular microwave laboratory who wants to implement an experimental setup of a MSS.

To our knowledge, expensive commercial vector RF signal generators are of great essentials for current MSS testing systems. In [25], 12 synchronized commercial RF signal generators and 12 phase shifters were used to build a MSS testing system. In [7], a Ku-band multicarrier generator was implemented based on 12 L-band vector signal generators and 12 Ku-band up-converters. But for us, all these difficulties can be solved with the UCMG proposed in this paper. The technique details of the PLLs based CMS is clearly introduced in next section.

3. Implementation of the UCMG

3.1 Principle

As a very important component for signal sources imple-

Fig. 4 Principle of new Fractional-N PLL

mentation, Fractional-N PLLs have been widely used to generate RF signals of many devices or microwave circuits [27, 28, 29, 30, 31]. However, limited with the design of PLL architecture, the output signals' frequency and phase of traditional Fractional-N PLLs are related parameters, which cannot be controlled as user's demand independently [32]. Recent studies solved this problem by introducing a cyclically shifting, the control word of frequency divider to a Fractional-N PLL. This improvement makes conventional PLLs can assign a certain value as the initial phase of the output RF signal, even if the output signal is predefined at different frequency. This is the technique that we use to implement the proposed UCMG.

As Fig. 4 shows that the phase control action is related with four control words (CW), i.e., the frequency CW, phase precision CW, and two phase-shift CWs (K_{p1} and K_{p2}). Firstly, K_{p1} and K_{p2} are sent to phase reset register. Then, they are written into delta-sigma modulators together with the phase CW. Finally, the modulated results of phase shift CWs and phase CW are added with the shifted frequency CWs respectively. Now, these frequency dividers (FDs) are worked out and written into the FD registers. According to [33], the frequency and phase shift control can be mathematically described by (4) and (5).

$$f_0 = f_r \cdot \{[N_f + (K_f - 1)/M] + 1/M\} \quad (4)$$

$$\Delta\varphi = 2\pi \cdot (K_{p1} - K_{p2})/M \quad (5)$$

where f_r is the reference frequency, f_o is the frequency of VCO. N_f , K_f , and M are the frequency and phase precision CWs, respectively. $\Delta\varphi$ is the phase difference between the outputs of the Fractional-N PLLs.

As a result, the phase difference $\Delta\varphi$ is only related with CWs K_{p1} , K_{p2} and M . When M is a constant, K_{p1} and K_{p2} can determine the phase difference, i.e. $\Delta\varphi$. According to (5), the phase control precision can be improved as needed by increasing the width of M theoretically. With the technique of programmable device and micro-processor, digital bit-width is no longer a limitation in digital control unit design, which can always have sufficient bit-width to meet system's requirements. Therefore, this technique can be well used to solve the difficulty in implementing the UCMG.

3.2 Implementation of UCMG

Figure 5 shows the implementation of the Fractional-N PLLs based UCMG. It consists of 12 channels of Fractional-N PLL based signal generator, one clock management module designed with a TCXO, one digital control interface and a configure software. As Figure 5 indicates, each channel of Fractional-N PLL signal generator includes a PLL module to generate assigned RF signal, a filter network to cancel the

Fig. 5 Details of UCMG architecture

noise and harmonic waves and a power management module to control the amplitude of RF signal's output power. The clock management module is designed to synchronize 12 channels' reference clock by dividing one input 10 MHz clock signal into 12 output clock signals, to make sure all 12 channels' output signal are coherent. In the digital control interface module, a pair of programmable MCU and CPLD are used transfer control words from configure software to Fractional-N PLL registers, acting as communication interface between control software and the UCMG.

In this paper, the Fractional-N PLLs were a commercial chip from ADI named ADF5355. Within a 24-bit CW in register 3, the phase of the RF output frequency can adjust in 24-bit steps, from $0^\circ(0) - 360^\circ(2^{24} - 1)$. In order to minimize the phase noise and jitter, we choose a high-stability TCXO from RAKON named RTX7050A to act as references clock of all 12 channels Fractional-N PLLs. In order to make sure all Fractional-N PLLs to be initialized at the same time, digital control interfaces designed with CPLD is used to trigger the locking action synchronously. As Figure 6 shows, all Fractional-N PLLs are fixed on the digital control interface module, where they can get power supply, control words, reference clock. To make the hardware details and chips selection more clear, the main commercial components used in this UCMG are listed in Table I.

With the design of the filter network and RF signal path, the UCMG can work in an ultra-wide frequency range from 300 MHz–18 GHz. Figure 7 shows the frequency spectrum of one Fractional-N PLL signal generator who works at 16 GHz. The used real-time spectrum analyzer is Agilent E4407B. From the data of spectrum analyzer, we can calculate the phase noise of the 16 GHz sinusoidal signal output from one channel of the proposed UCMG with equation (6) [34].

$$L(f) = P_n(\text{dBm/Hz}) - P_s(\text{dBm}) - 10 \log(1.1 \times \text{RES.BW}) \quad (6)$$

Where, P_n indicates the noise power in a 1 Hz bandwidth, and P_s indicates total signal power in test bandwidth. The calculated result shows that the phase noise of proposed UCMG is -75 dBc/Hz @ 1 kHz, -82 dBc/Hz @ 10 kHz, -84 dBc/Hz @ 20 kHz, which is satisfactory for the strict requirement of a MSS. Since the waveform jitter is mainly related with the phase noise of each carrier, we can draw the conclusion that multicarrier signal combined with proposed UCMG would be very stable.

Fig. 6 Fractional-N PLLs based UCMG

Table I Key Components Used in the UCMG

Device	Manufacture	Function
ADF5355	ADI	PLL
STM8AF6286	ST	Microprocessor
EPM570T144C4	ALTERA	CPLD
RTX7050A	RAKON	TCXO
HMC573	ADI	Frequency Multiplier
HMC311	ADI	Low-Noise-Amplifier
HMC3653	ADI	Low-Noise-Amplifier
HMC451	ADI	Low-Noise-Amplifier
HMC1019	ADI	Attenuator

4. Result and in-system calibration

Figure 8 shows the experimental setup of the testing of the implemented UCMG, of which six channels are assigned to output a series of 6-carriers signal in “in-phase” mode, the other six channels are assigned to output a series of 6-carriers signal in “triangle-phase” mode. Two combined coherent multicarrier signals were sent to a wideband oscilloscope with 2.5 GS/s sampling rate. The frequency of the first carrier is set as 800 MHz, and Δf_j is set as 1.25 MHz.

One thing that has to be mentioned is that, even though we design and assemble each channel of Fractional-N PLL signal generator all the same. The phase delay and amplitude between different channels are still can hardly be unbalanced, which will result in waveform distortions of the combined signals inevitably. Now, the advantage of pro-

Fig. 7 Frequency spectrum of FPLL

Fig. 8 Experimental setup of the proposed UCMG

Fig. 9 Waveforms of the 6-carrier “in-phase” and “triangle-phase” signals

posed UCMG in channel phase adjustment can be useful to solve this problem with a three-step in-system calibration.

Firstly, the output multicarrier signal of UCMG will be sampled with a wideband instrument, like the oscilloscope we use in this experiment. Secondly, we use an inverse Fourier transform of the sampled data to acquire the phase and amplitude of each channel, and the phase and amplitude error among each channel can be retrieved by comparing them with the predefined ones. Finally, a negative feedback mechanism is introduced to calibrate the unbalanced phase delay and amplitude among different channels.

Figure 9 shows the photographs of the 6-carrier “in-phase” and “triangle-phase” multicarrier signals output from the 12-channel UCMG after such an in-system calibration. The

Fig. 10 An example of MSS setup with proposed UCMG

experiment result shows that these signals are nearly the same with the waveform shown in Figure 3, which have the same carrier configuration as the experimental setup.

In Figure 10, an example of MSS experimental setup based on proposed UCMG is demonstrated, according to implementation in Figure 1. Compared with current methods that use a series of expensive microwave instruments to setup MSS, the UCMG proposed in this paper is compact, low-cost, and satisfactory for experimental usage. It makes MSS related research an affordable field for ordinary microwave laboratory. What's more, it can also bring significant convenience and quantitative measurement of multipactor threshold for any multicarrier waveforms, with the functions of digital control system and in-system calibration technique.

5. Conclusions

As the most important and complex part of a conventional MSS, we demonstrate a novel, cost-effective approach to design a 12-channel ultra-wideband coherent multicarrier generator for the experimental setup of MSS. With design of the state-of-the-art Fractional-N PLLs system and in-system calibration techniques, the UCMG can take the place of MSS's complex coherent multicarrier generation system which requires numbers of RF vector generator and a synchronize clock. What's more, the UCMG can work from UHF to KU band with each carrier's phases, frequencies and amplitudes predefined and adjusted independently. It can act as an experimental instrument for many microwave laboratories because of its economy, wide-band feature and satisfactory performance. It will help to promote in-depth experimental research on the multipactor threshold measurement and related area.

Acknowledgments

This work was supported by the NSFC under grants 61701437.

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