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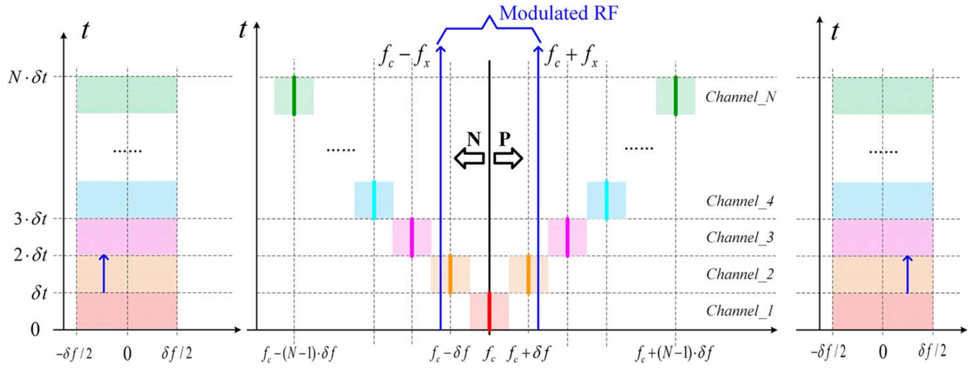

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# Photonics-Assisted Serial Channelized Radio-Frequency Measurement System With Nyquist-Bandwidth Detection

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**Abstract:** Based on serial channelization and coherent detection, a radio-frequency (RF) measurement scheme with a Nyquist-bandwidth detector is proposed and experimentally demonstrated. With a wavelength scanning structure, multiple RF channels serial in the time domain are implemented. A coherent receiving module based on an optical hybrid and balanced photodetectors (BPDs) is constructed to reduce the receiver bandwidth and the bandwidth of the follow-up electronic devices. In this paper, a six-channel 3-GHz-spacing channelizer, with 18-GHz receiving bandwidth and 1.5-GHz BPD, is demonstrated. In addition, multifrequency signals and a linear frequency modulation signal with the slope of 4.53 MHz/$\mu$s are tested.

**Index Terms:** Radio-frequency measurement, wavelength scanning, serial channelization.

## 1. Introduction

In radar system and electronic warfare, broadband frequency measurement has attracted much attention for its massive applications. Recently, a lot of photonic-assisted radio frequency measurement schemes have been proposed for its advantages in wide bandwidth, low loss, and so on [1]. There are several schemes based on the different transmission responses of frequency-to-power mapping, for example, using optical filters to get power comparison [2], based on simultaneous phase modulation and intensity modulation [3], using a polarizer and a Mach-Zehnder interferometer (MZI) in one branch [4], or two optical wavelength sources and two dispersion fiber segments in different channels [5]. Also, transversal microwave filters with sine and cosine frequency responses is used in different branches to construct the frequency-dependent amplitude comparison functions [6]. An ingenious frequency scanning measurement system is achieved based on stimulated Brillouin scattering, which also maps multiple frequencies to power change [7], but the resolution is limited by Brillouin bandwidth and scanning

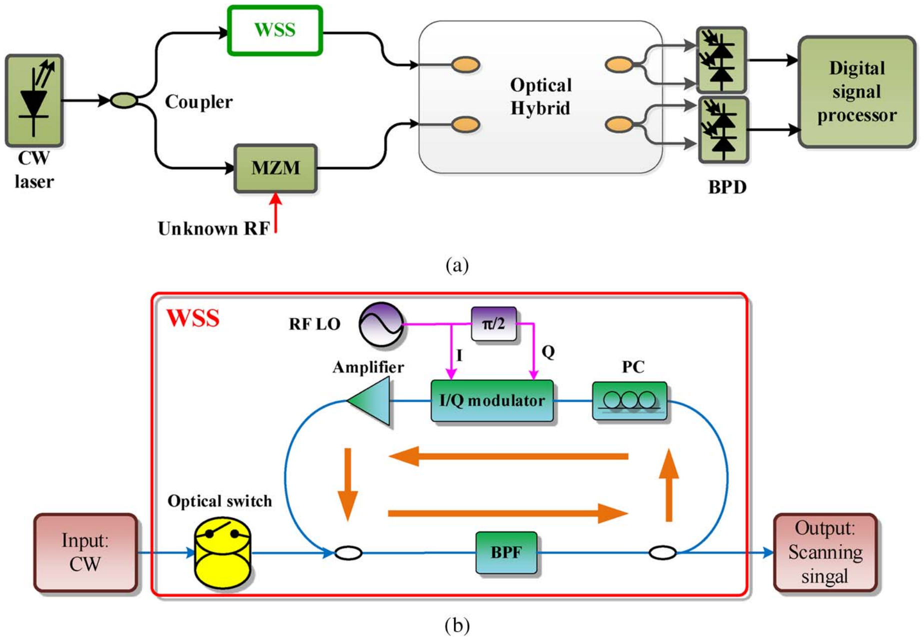

Fig. 1. (a) Schematic of the proposed serial channelized coherent receiver system based on WSS. (b) Inner structure of the WSS; MZM: Mach-Zehnder modulator; WSS: wavelength scanning structure; I/Q: in-phase/quadrature; BPF: band-pass filter.

interval and scan rate is unsatisfactory. To realize flexible measurement, RF channelizer with reconfigurable operating bandwidth and channel space is realized based on a 2-pump self-seeded parametric mixer and Fabry-Perot etalon [8], and two optical frequency combs and I/Q demodulation [9], but perfect alignment is necessary, and the structure is complex for multiple photo-detectors (PD) or multiplexers being employed in these schemes.

Recently, we have proposed a novel concept of serial channelization based on optical wavelength scanner called OSCAR [10]. In the wavelength scanner, every frequency exists in corresponding time window, so channelizing in frequency domain and time domain are realized simultaneously when the scanning signal is used as local oscillator (LO) of down-conversion. And thus channels are constructed serially in time domain and beat notes are acquired in some channel in specific time interval. Serial channelization simplifies the structure since filter banks are not necessary to divide channels and only a transmission path and a receiving device are needed. In this paper, we proposed a receiving module based on an optical hybrid and balanced detectors to further reduce the receiver bandwidth to half of the channel, which we called Nyquist bandwidth. Based on the proposed scheme, the frequency identification process can be simplified and easy to realize for real-time RF frequency measurements.

## 2. Principle

The principle of the scheme is briefly described in Fig. 1(a). The output of a continuous wavelength (CW) laser is divided into two parts, one part is fed into the WSS and the other part is intensity modulated with an unknown RF signal. Then, the two branches are coupled into an optical hybrid and the output subsequently enters a narrow-band balanced power detector (BPD) and coherently received and detected.

The inner structure of the WSS is shown in Fig. 1(b). The WSS is realized based on a recirculating frequency shifting (RFS) loop [11] and an optical switch [12]. Firstly, the input CW is carved to pulses by the optical switch. And the switch is externally electric-controlled to ensure that duration of an individual pulse is equal to the round-trip time of the RFS loop. Then, the optical pulses are injected into the RFS loop and modulated with a RF LO signal by a complex I/Q modulator. Under the condition of single sideband carrier-suppressed modulation, as the optical signal travels around the loop, its instantaneous frequency will shift with a step equal to the RF LO in every round trip. A band-pass filter (BPF) is used to limit the bandwidth of the scanning signal and an erbium doped fiber amplifier (EDFA) is used to compensate the loop loss. As a result, the output of the loop is a scanning signal whose frequency shift interval is equal to RF LO, hold time of an individual frequency is equal to loop round-trip time and scanning period is equal to optical switch's on-off period. Clearly, the bandwidth of the BPF and RF LO collectively determine the scanning range, which can be easily readjusted.

Assuming the scanning signal in time window of $[(k-1)\cdot\delta t, k\cdot\delta t]$ is expressed as (1), shown below, and the modulated RF signal is expressed as (2), shown below:

$$S_S(t) = A_k \exp[2\pi(f_c \pm (k-1)\cdot\delta f)\cdot t] \tag{1}$$
$$S_{RF}(t) = B\cdot\exp(2\pi f_c\cdot t). \tag{2}$$

$f_c$ is the CW frequency, and $f_k$ represents the kth frequency of wavelength scanning signal and $f_k = f_c \pm (\mathrm{k}-1)\cdot\delta f,\ k = 1, 2, \ldots N$. Here, we consider the plus sign one (corresponding to positive frequency scanning, which will be explained in the following). According to the transmission characteristic of the optical hybrid and BPD, the output of the two BPDs can be expressed as

$$\begin{aligned}\begin{bmatrix} I(t) \\ Q(t)\end{bmatrix} &= \begin{bmatrix} |S_S(t)+jS_{RF}(t)|^2 - |jS_S(t)+S_{RF}(t)|^2 \\ |jS_S(t)-jS_{RF}(t)|^2 - |-S_S(t)-S_{RF}(t)|^2\end{bmatrix} \\ &= \begin{bmatrix} A_k\cdot B\cdot\sin[2\pi(k-1)\cdot\delta f\cdot t] \\ A_k\cdot B\cdot\cos[2\pi(k-1)\cdot\delta f\cdot t]\end{bmatrix}.\end{aligned} \tag{3}$$

Neglecting the constant during the derivation, we could get the received signal from (3) as

$$j\cdot I(t) + Q(t) = A_k\cdot B\cdot\exp[j\cdot 2\pi\cdot(k-1)\cdot\delta f\cdot t]. \tag{4}$$

From (4), we can see that the result of the detection is just ideal downconversion of the unknown RF signal. What we have to emphasized is that, benefit from the coherent detection structure (hybrid + BPD), the downconversion of the unknown RF signal is realized by multiplying an e-exponent function but not circular function. So, there will be no mirror components after the downconversion. Compared with the scheme with only one BPD [10], there will be no “frequency ambiguity” problem here anymore, which could greatly simplify the strategy of frequency identification.

Then we analyze the frequency domain of the measurement system. The WSS's time-frequency characteristic is shown as Fig. 2(a). There is a unique frequency in every time window of $\delta t$, and the frequency shifts from $f_c$ to $f_c + N\cdot\delta f$ (P: positive scanning) or $f_c - N\cdot\delta f$ (N: negative scanning) with a step of $\delta f$ in a scanning period of $N\cdot\delta t$, where $f_c$ is the first frequency of WSS. As frequency scanning, channels serial in time domain is constructed (see shadow areas in Fig. 2). Assuming that the modulated RF signal lies in the positions shown in Fig. 2(a) (blue arrow lines), received beat notes should be located at positions (blue arrow lines) illustrated in Fig. 2(b) in N scanning or in Fig. 2(c) in P scanning after I/Q demodulation processing. In fact, they can be expressed as (5) (N scanning), shown below, and (6) (P scanning), shown below:

$$f_1 = (k-1)\cdot\delta f - f_x \tag{5}$$
$$f_1 = f_x - (k-1)\cdot\delta f \tag{6}$$

where $f_1$ is detected beat frequencies here in the second channel. Beating “direction” of a certain channel is determined by the wavelength scanning direction, meaning that for beat notes in this channel, we can ascertain which equation between (5) and (6) should be used to resolve the to-be-measured RF. Because of balanced detection and I/Q demodulator, only one

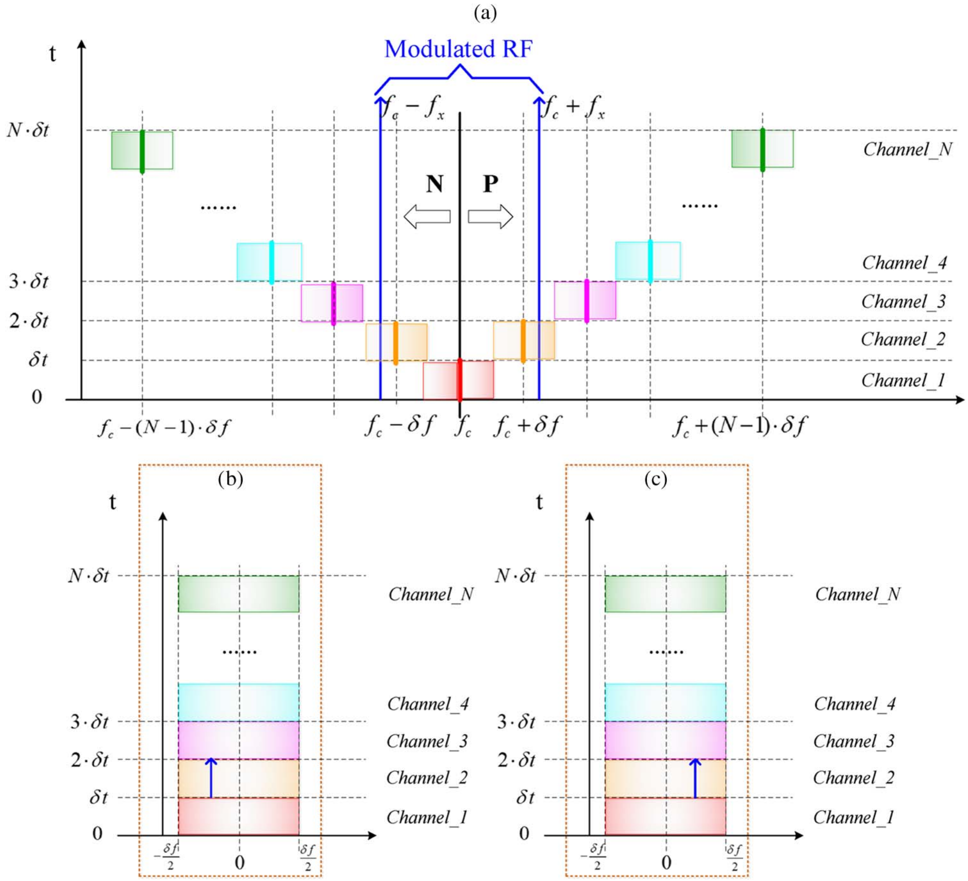

Fig. 2. Time-frequency diagrams of (a) the WSS's frequencies (colorful solid lines) and modulated RF (blue arrows); (b) identify RF frequencies in negative frequency scanning by (5); (c) identify RF frequencies in positive scanning by (6). Colorful shadow areas represent time-frequency range of different channels.

channel's beat notes are necessary and the receiving bandwidth could be reduced to be $\delta f/2$, which is enough to recover the unknown radio frequency, and the Nyquist bandwidth $(\delta f/2)$ is also the minimum bandwidth required in such a system; therefore, it allows low-speed receiving module needed in the proposed measurement system. For k-th channel, the strategy of frequency identification is shown in Fig. 3.

## 3. Experimental Results

In the experiment, the scanning space of WSS is 3 GHz which is also the channel bandwidth and the receiver bandwidth is set to be 1.5 GHz correspondingly. The hold time of a single frequency is 200 ns in our experiment, so the resolution is 5 MHz in theory. The WSS contains 6 wavelengths scanning in a whole period of 1.2 $\mu$s, meaning that the system holds six channels with 833 kHz scanning rate in a frequency measurement range of 18 GHz. Fig. 4 shows the experimental results of multi-frequency RF signal which consists of discrete frequencies at 1.2, 2.4, 3.7, 4.5, and 5.6 GHz. As expected, the corresponding beat notes are received in corresponding channels with certain direction, which is negative direction in our experiment. It means we should use (5) to recover the frequency. For example, the detected frequency in 1st channel is $-1.2$ GHz, so the actual frequency $f_x$ is $(1-1) \times 3$ GHz $- (-1.2$ GHz$) = 1.2$ GHz. Thus, from Fig. 4, one can see that in the 1st channel at $-1.2$ GHz, the 2nd channel at 0.6, $-0.7$, and $-1.5$ GHz, the third channel at 1.5 and 0.4 GHz. Therefore, the frequencies can be identified correctly according to (5), as shown in Fig. 4(d).

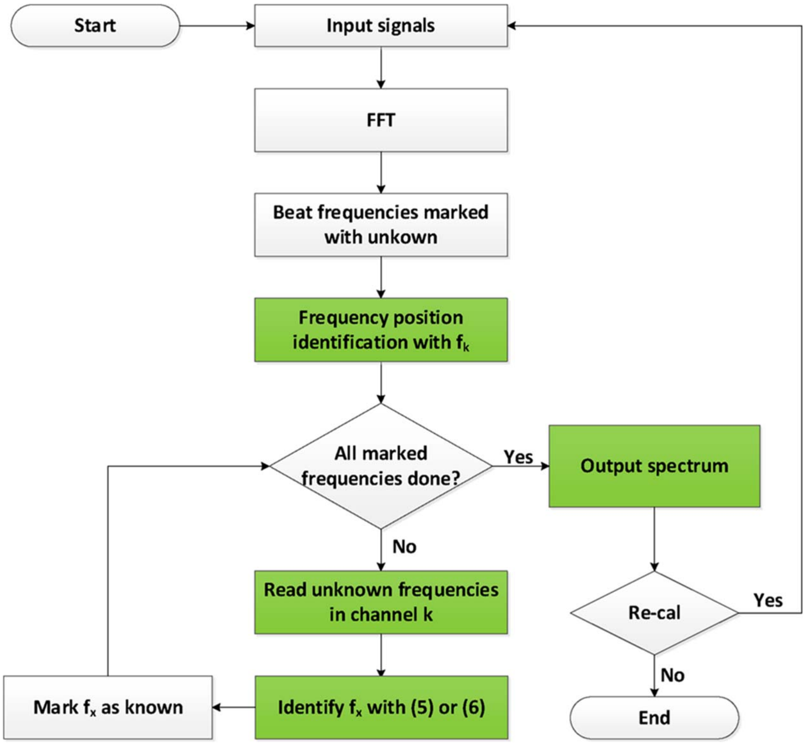

Fig. 3. Flow chart of strategy of frequency identification in the kth channel.

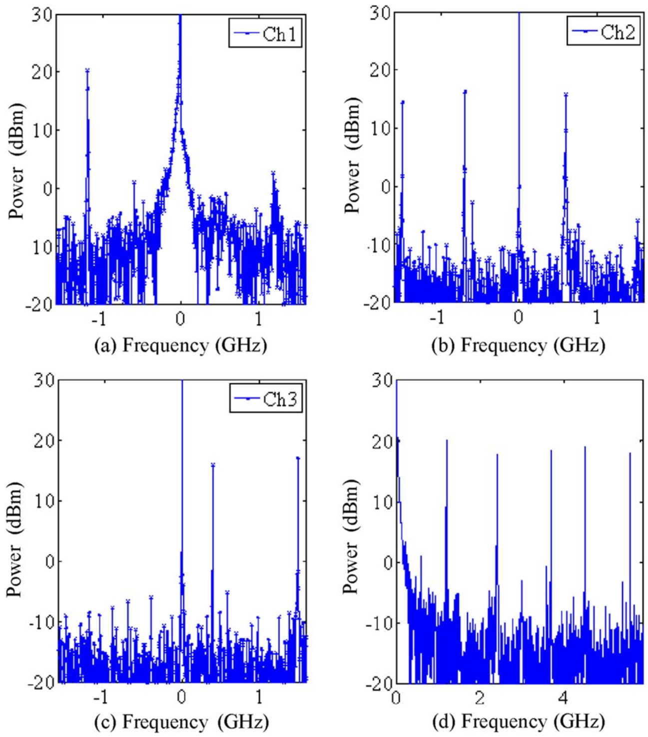

Fig. 4. Beat notes in the (a) first, (b) second, and (c) third channel of multi-frequency signal. (d) The recovered multi-frequency RF signal.

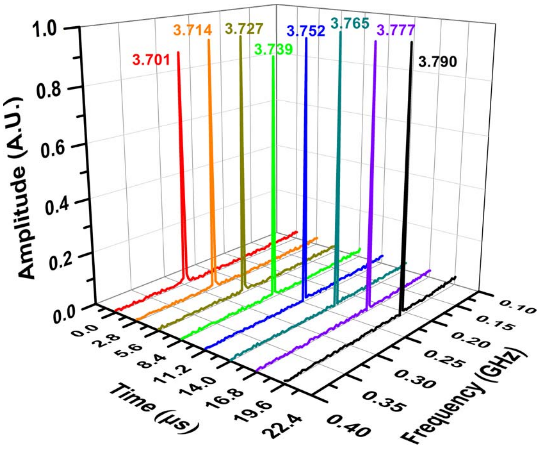

Fig. 5. Diagram of tested LFM signal in the third channel.

Also, we build another RF measurement system with seven-channel 2-GHz-spacing 400-ns-loop-period to test linear frequency modulation (LFM) signals. An LFM pulse with tens-of-$\mu$s temporal width can be captured in several measurement periods. The LFM slope can be obtained by calculating beat frequencies in a certain channel of adjacent periods. A periodic LFM pulse of 102-MHz bandwidth (from 3.7 GHz to 3.802 GHz) is used, with pulse width and LFM slope being 22.5 $\mu$s and 4.53 MHz/$\mu$s respectively. The time-resolution for LFM measurement is 2.8 $\mu$s, which is equal to the period of the scanner. Frequency-range of the LFM signal could be estimated related to LFM slope and time-resolution. Therefore, the maximum error of the measured LFM signal's frequency range in the experiment is 4.53 MHz/$\mu$s $\times$ 2.8 $\mu$s $=$ 12.68 MHz. Beat notes should be detected in serial 8 scanning periods. As shown in Fig. 5, beat notes in the third channel (center frequency $=$ 4 GHz) are received in 8 serial periods. There's a frequency change of 12.7 MHz in one scanning period of 2.8 $\mu$s and thus the LFM slope is calculated to be 4.54 MHz/$\mu$s. Because the resolution is 2.5 MHz (corresponding to 400 ns-loop-period), we obtain a frequency change of 12.7 MHz other than 12.68 MHz, which causes the error between the recovered LFM slope of 4.54 MHz/$\mu$s and the original slope of 4.53 MHz/$\mu$s.

As shown in Fig. 2(a) and (4), it is clear that the measuring procedure of the proposed system is highly dependent on the status of the WSS. The frequency of the WSS serially scans across the whole measuring range temporally, and the receiving bandwidth of the system is limited, which is far narrower than that of the unknown RF signal. Therefore, the measuring result we get in each channel actually is only a spectral slice of the unknown RF signal, which is equivalent to sampling in frequency domain. Take the measuring result of the LFM signal in Fig. 5 as an example. In (5), at the zero-time point, the measured frequency of the LFM signal is 3.701 GHz. This only indicates that at this time the unknown signal has frequency component at 3.701 GHz, but there may be some other frequency components we missed because the receiving bandwidth is not wide enough. Therefore, similar to the Nyquist sampling theorem, the effectiveness of the proposed scheme is based on that the frequency variation of the unknown RF signal is slow compared with the period of the WSS. More specifically, the duration of each frequency component in the unknown RF must be long compared with the period of the WSS, so we could get sufficient samples to reconstruct the unknown RF signal. The slope of the frequency changing of the unknown RF signal must be much smaller than that of the WSS, so we will not miss the details of the frequency changing. Accelerating the scanning speed of WSS will be helpful for the system to better measure the RF signal with short duration or drastic frequency variation. However, this will sacrifice the precision of the measurement, because the frequency resolution is inversely proportional to the period of the WSS. Therefore, there is trade-off in realistic application. We have to choose appropriate parameter for the system after considering the requirements of both the speed and precision.

## 4. Conclusion

In this paper, based on serial channelization, coherent detection and I/Q demodulation, an RF measurement structure is proposed and experimentally demonstrated. The scheme extend the advantage of the OSCAR system with Nyquist-bandwidth detection. It highly simplifies the frequency identification strategy and relieves the requirements for electrical devices. As proof, we build RF measurement systems with loop period of 200 ns and 400 ns respectively. A six-channel, 3-GHz-space channelizer with 1.5 GHz receiving bandwidth is demonstrated. Also, a linear frequency modulation signal is tested within 14 GHz bandwidth with the slope of 4.53 MHz$/\mu$s. With simple structure, this system is promised to extensible measurement range and further improvement in various RF frequency measurements applications.

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