Four-wave mixing based phase-conjugation technique for retro-directive array

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Abstract: A retro-directive arrays based on the optical Four-Wave Mixing (FWM) technique was proposed. This kind of arrays automatically tracks mobile terminal without phase shifters. Normal self-tracking action is based on phase-conjugating mixing circuit in smart antenna and phased array antenna. A new method was suggested for phase-conjugation which relies on FWM technique to solve the problems in the radio frequency circuit and design the structure of this system afterward. Finally, the working principle of SOA was analyzed and the appropriate parameters was designed to ensure that the phase-conjugating RF signal intensity can make the transmitting antenna array work normally.

Key words: distributed fiber optic sensor; pattern recognition; SVM

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基于四波混频相位共轭技术的方向回溯天线设计

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摘 要: 提出了一种基于光学四波混频技术的方向回溯天线阵。这种类型的天线阵能够在不使用移相器的情况下自动追踪移动终端。现有的智能天线和相控阵天线的自动追踪功能是基于相位共轭混频电路实现的。提出了一种更新的基于四波混频技术的相位共轭的实现方法,以解决原有方法在射频电路在设计和结构上出现的问题。最后分析了半导体光放大器(SOA)的工作原理,并设计合适的参数以确保产生的相位共轭射频信号强度能够满足发射天线阵正常工作的要求。

关键词: 微波光子学; 方向回溯天线阵; 光学相位共轭

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0 Introduction

Recently, many RF systems have been designed with directed beam-forming capabilities. Phased array antennas that can greatly improve the performance of mobile communication systems have been studied extensively[1]. In the case of directed transmission, phase shifters are used in phased array and smart antenna systems to perform beam tracking[2]. Several designs for photonic phase shifters have been demonstrated based on heterodyne mixing[3]. Due to its cost effectiveness and compactness, the retro-directive array has been of particular interest. A retro-directive array transmits a signal back to the interrogator's position automatically without any apriori knowledge of the incoming angle or relying on the digital signal processing algorithms[4].

The phase-conjugating mixing circuit became a main method used for achieving retro-directivity[5]. However, there are some problems in this solution, such as the difficulty to make mixers in high frequency and the electromagnetic leakage, etc. In this paper, an optical method is presented using Four-Wave Mixing (FWM) technique as a substitute to produce phase-conjugated RF signals. The received RF signals are modulated onto the optical carriers in order to be processed by optical devices and transformed into phase-conjugating signals.

1 Phase-conjugation in retro-directive array

When the sum of the signal phase of transmitting and receiving element is a constant: $\varphi_i^t+\varphi_i^r=\mathbf{C}$, the antenna array can achieve the retro-directivity. This is the generalized phase-conjugating condition[6]. When the constant $\mathbf{C}=0$, it is transformed into $\varphi_i^t=-\varphi_i^r$, where φ_i^t and φ_i^r are the signal phase of transmitting and receiving element. As it shows in Fig.1.

To achieve the phase-conjugating condition automatically, the received signal at each element is processed by phase-conjugating circuitry: a mixer driven from a local oscillator (LO) at twice the RF frequency takes the difference of the phases of the RF and LO signals. The module ultimately achieves the phase-conjugation after band pass filtering. Then the signals will be reradiated to the source direction.

$$\mathbf{V}_{\mathbf{OUT}}(t)=\mathbf{V}_{\mathbf{IF}}(t)\propto\mathbf{V}_{\mathbf{RF}}\cos(\omega t+\varphi)\mathbf{V}_{\mathbf{LO}}\cos(2\omega t)=$$

$$\frac{1}{2}\mathbf{V}_{\mathbf{RF}}\mathbf{V}_{\mathbf{LO}}(\cos(3\omega t+\varphi)+\cos(\omega t+\varphi)\overset{\mathbf{BPF}}{\longrightarrow}\cos(\omega t-\varphi)\quad(1)$$

It's hard to get the LO, if the RF signal works at high frequency. And also, the IF signal is the same as that of the RF signal, making it difficult to separate the two signals with a filter[7]. The feed network is another problem, because of its electromagnetic radiation interference to the directivity diagram. Therefore, an optical process method is proposed to deal with these problems.

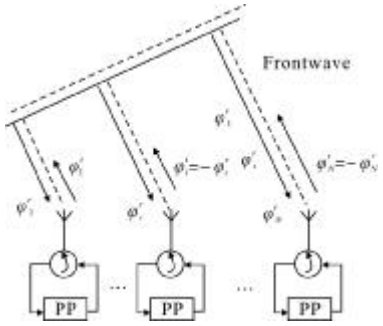

Fig.1 Phase-conjugating antenna array

2 RF phase-conjugation based on optical methods

In Fig.2, the optical signal (LD) is modulated

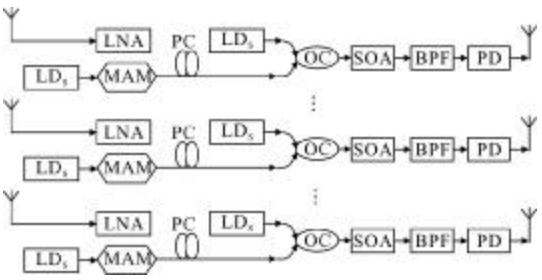

Fig.2 Optical phase-conjugating system

with received RF signal by a dual-drive Mach-Zehnder modulator (MZM). The optical signal can be expressed as $\mathbf{E}_{in}=\mathbf{E}_{in}e^{j\omega_s t}$, where ω_s is the frequency of optical carrier. The expression of input RF signal is $v(t)=V\cos(\Omega t+\theta)$, where Ω and θ are the frequency and phase of RF signal. The optical signal after double-sideband modulation is given by

$$\mathbf{E}_s(t)=\mathbf{E}_{in}\cos\left[\frac{\pi}{4}+\beta\pi\cos(\Omega t+\theta)\right]\exp\left(i\frac{\phi_1+\phi_1}{2}\right)\approx$$

$$\mathbf{E}_0\left[\mathbf{J}_0(\beta\pi)e^{j\omega_s t}-\mathbf{J}_1(\beta\pi)e^{j[(\omega_s-\Omega)t+\theta]}-\mathbf{J}_1(\beta\pi)e^{j[(\omega_s-\Omega)t-\theta]}\right] \quad (2)$$

Where $\mathbf{J}_0$ and $\mathbf{J}_1$ is the Bessel function. Output signal contains the optical carrier and the first-order sideband, and the high-order sideband is ignored. In order to achieve RF phase conjugation, the semiconductor optical amplifier (SOA) is used to process optical signals, because its features such as high nonlinear coefficient, wide working band, easy integration, etc. The optical signal and pump wave are injected into SOA at the same time. A new wave ($\lambda_c=2\lambda_p-\lambda_s$) was generated because of the nonlinear FWM effect in active waveguide[8]. The new wave's upper and lower sideband inversion is realized as it can be seen in Fig.3.

$$\mathbf{E}_c(t)\propto$$

$$\mathbf{E}_0\left[\mathbf{k}_0(\beta\pi)e^{j\omega_s t}-\mathbf{k}_1(\beta\pi)e^{j[(\omega_s-\Omega)t-\theta]}-\mathbf{k}_2(\beta\pi)e^{j[(\omega_s-\Omega)t+\theta]}\right] \quad (3)$$

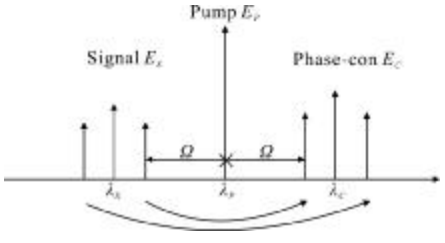

Fig.3 Generation of phase-conjugating wave

The signal intensity after demodulation can be expressed as equation (4). Finally the phase-conjugating RF signal after band pass filtering is got.

$$I=\mathbf{E}_0\cdot\mathbf{E}^*\propto C+C_1\cos(\Omega t-\theta)+C_2\cos(2\Omega t-2\theta)\xrightarrow{BPF}C_1\cos(\Omega t-\varphi) \quad (4)$$

3 Parameter design and simulation is analyzed and designed

The appropriate parameters are analyzed and designed to ensure that the phase-conjugating RF signal intensity can make the transmitting antenna array work normally. The major influence factors include the power and the frequency-difference of pump and signal. For a certain optical signal power, the pump power has an optimum value. Though it enhances the nonlinear effect of SOA, the increase of pump power will lead to SOA gain saturation eventually. So does the signal wave. When the frequency-difference of pump and signal increases, SOA's nonlinear efficiency reduces because of the phase mismatch. Therefore it should be limited within a certain range[9].

The simulation shows the feasibility of this method. The pump and signal power is 5.6 dBm and 1 dBm. We choose 0.037 THz as the frequency-difference of pump and signal wave. The frequency of RF signal is 5 GHz, and its initial phase is 30°. As Fig.4 shows, the phase of output signal is -30°. The RF signal phase-conjugation is achieved by the optical processing module.

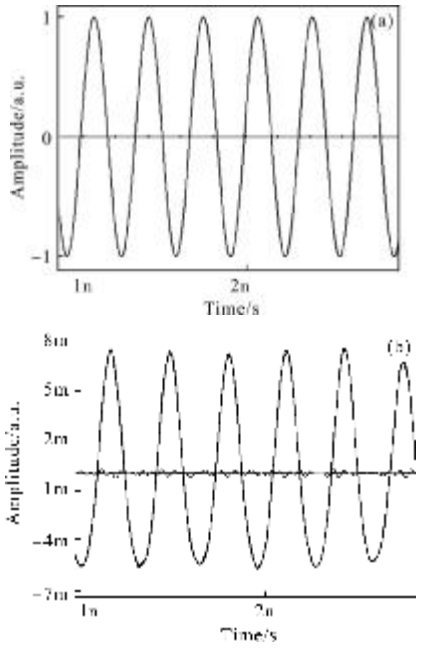

Fig.4 Oscillogram of input and output signal

4 Conclusion

A design for a retro-directive antenna array based on optical FWM technique was proposed and tested. The normal phase-conjugating solution and implement a modified optical system were reviewed. The simulation shows that the phase-conjugating was being utilized. The newly developed retro-directive array will be useful in high frequency communication and other applications due to its broadband characteristics[10]. Further improvements should start from better performance and structure and develop the full duplex communication function for the application.

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