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Optical assisted digital-to-analog conversion using dispersion-based wavelength multiplexing

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ABSTRACT

A simple scheme of optical assisted digital-to-analog conversion which utilizes multiwavelength multiplexing is proposed. The output of multiple electronic digital-to-analog convertor are modulated on optical carriers with different wavelengths and sampled by ultrashort pulse train. The multiwavelength sampling pulse train is rearrange by dispersive device to complete conversion output A 7-bit experiment system with a conversion speed of about 8 GS/s demonstrates the feasibility of the proposed scheme. The conversion accuracy is greater than that in traditional intensity weighting and summing structure. By designing the input bits properly, arbitrary waveforms can be generated. The relative factors and potential performance are discussed.

1. Introduction

Digital to analog conversion, which allows the user to generate a desired analog signal with binary data, is a critical function for numerous modern signal-processing applications, including arbitrary waveform generation, high-speed communication, sensor networks, wideband radars and electronic countermeasure [1,2]. However, electronic solutions for digital-to-analog convertor (DAC) suffer from high timing jitter and electromagnetic interference, which are the inherent disadvantages of electronic system. Traditional electronic schemes cannot meet the increasing demands of future systems due to the dramatic growth for signal data size [3,4]. Owing to immunity to electromagnetic interference, high speed and broadband nature, optical digital-to-analog convertor (ODAC) has drawn increasing attention in recent years. ODAC provides not only a higher performance approach, but also a high compatibility with the optical fiber communication networks, which are widely used in many civil and military applications [5–7].

Optical waveform synthesis in time domain is a promising solution to realize OAWG with high flexibility. The core component is optical digital-to-analog convertor (ODAC), which performs conversion between digital data and analog signal by optical methods. With appropriate digital input, the temporal duration and waveform profile parameters of analog signal can be easily set. Along with the high speed and wide bandwidth, ODACs have been used in many applications for the compatibility with other fiber systems.

Several approaches have been researched: multi-channel intensity weighting and summing [8–10], digital synthesis in multi-electrode Mach–Zehnder interferometer [11], coherent summation of optical phase-modulated signals [12] and polarization multiplexing in dual-polarization modulator [13]. The basic concept for those techniques is weighting the intensities of multiple optical carriers and summing them according to electrical digital signals. The frameworks of those methods are easy to build, but the bit resolution is limited by the performance of light source and the accuracy is limited by the mismatching between multiple channels in practical use. Optical pulse pattern recognition [14,15], all-optical logical operation [16], optical differential phase shift keying modulation and balanced detection [17] and Silicon micro-ring resonator [18] provide other ways to make ODAC available. But the number of optical devices increase exponentially as the bit resolution grows. According to the operation principle, those schemes can also be divided into two types: parallel operation mode and serial operation mode. Parallel ODACs can reach a higher bit resolution by accumulating parallel channels, and the speed requirement of optical devices in each channel can be decreased. However, the number of channel and system complexity grows with the increasing bit resolution, which increases the system cost and the difficulty of synchronous operation. The schemes of serial ODAC are more compact, and fewer optical devices, such as modulator, are needed [19]. The drawback of serial ODAC is that the speed and bit resolution are limited by device's performance. Although the speed of ODAC is higher than electronic DAC (EDAC) for one or two orders of magnitude, the bit resolution of the ODAC reported is about 4∼6 bits, far less than EDAC for the restriction of the performance of optical devices. In this paper, we proposed a multi-channel optical assisted digital-to-analog convertor based on optical analog multiplexing, which combines the high speed of photonic technique with the precision of electronic technique. The output of several EDACs is modulated on optical carriers with different wavelengths. After that, a modulator driven by sampling pulse train is

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used to extract intensity information. Then, the pulse train is realigned by the group velocity dispersion (GVD) in optical fiber. The operation mode and bit resolution of this system are decided by electronic part, and the conversion speed is multiplied by optical multiplexing.

The paper is organized as follows: an introduction of the ODAC concept is in part 2. Part 3 describes the experiment and the performance of the established ODAC in detail. In part 4, the results are discussed and the factors are analyzed.

2. Principle

The schematic diagram of the proposed ODAC system with eight EDACs inside is shown in Fig. 1. The electronic part consists of eight EDACs with a conversion speed of f GS/s and a high-speed field programmable gate array (FPGA). The input digital codes are fed into FPGA in groups of eight. The bit resolution and data mode are decided by the used EDAC. Subsequently, digital codes are distributed synchronously to corresponding EDAC. EDACs convert digital code to proportional analog signal with a temporal width of ΔT ($\Delta T = 1/f$). With eight direct modulation lasers (DML), the analog output of each EDAC is modulated onto continuous wave optical carrier at different wavelength (from λ_1 to λ_8). The wavelength spacing ($\Delta\lambda$) between two adjacent DMLs is identical. And each DML works at the same initial state, too. Intensity-modulated optical signals at different wavelengths are combined in a wavelength division multiplexer (WDM).

The point A in Fig. 1 shows the state of the time-domain signal after WDM. Eight optical waveforms, which represent the eight digital codes in one group, are overlapped in the same time window with a temporal width of ΔT. After that, the mixed signal is processed in single channel, which simplifies the structure of system and eliminates the need of multi-channel matching. The multi-wavelength signal is modulated by a Mach–Zehnder modulator (MZM) driven by the sampling pulse train with a repetition rate of f and a pulse width of $\Delta\tau$. The MZM works in on–off mode. As shown in point B in Fig. 1, the output pulse train records the intensity information of all different wavelengths proportionately. To capture the intensity information as accurately as possible, an optical tunable delay line (OTDL) is used to adjust the sampling position to the middle point of time window. After modulation, the multi-wavelength pulse train passes through a dispersion medium. Due to group velocity dispersion, the eight components at different wavelengths are separated in time domain after propagation. The time spacing T_D is given by:

$$T_D = D \cdot L_D \cdot \Delta\lambda \tag{1}$$

where D is the dispersive index of dispersion medium and L_D is the length of dispersion medium.

By properly setting the chromatic dispersion and wavelength spacing to make T_D equal to ΔT/8, a time and wavelength interleaved optical pulse train with a repetition rate, which is 8 times higher than the original one can be generated as shown in point C in Fig. 1. To avoid inter-channel crosstalk, the pulse width of sampling optical pulse $\Delta\tau$ must be less than ΔT/8. The optical intensity of each pulse is proportional to the value of corresponding input of digital codes. The optical pulse train is converted to electronic signal by a photodetector. With properly designing the input digital code, specific waveforms can be generated based on this ODAC. The additional electrical low pass filter (LPF) is used to smooth the waveform as shown in point D in Fig. 1. The bandwidth of proposed ODAC is the product of the number of channels and the bandwidth of EDACs in theory, which is also limited by the bandwidth of optical devices used in practice.

The main concept of our scheme lies in the combination of electronic and optical technique. At current technical level, electronic devices have a higher bit resolution at low speed than optical systems. In all-optical DAC system, such as the system displayed in [19], high-power optical source is necessary for high bit resolution. But the consequent nonlinearity degrades conversion accuracy dramatically. So, the bit resolution of all-optical DAC is limited. While, it is an effective way for realization high bit resolution at high conversion speed to accelerate the operation speed of EDAC via optical means. The EDAC technique is mature. It is easy to add more EDAC channels into our scheme to reach higher conversion speed with little change in system structure. The cost of adding EDAC channels is much lower than that of eliminating nonlinearity in all-optical DAC system. The system structure is simple, and the devices used can be easily integrated.

3. Experiment and results

An 8-channel serial optical assisted digital-to-analog convertor system is established in order to validate the feasibility of the proposed scheme. The electronic part is comprised of eight EDACs (TI, DAC39J84) and an FPGA (Altera, Arria V GZ), those EDACs are synchronously controlled by the FPGA. The bit resolution of the input digital data can be the same high as the EDACs used in theory. Taking the power fluctuation of different optical channels into consideration, the designed bit resolution of the ODAC, which is established in our experiment, is set to 7-bit to avoid error codes introduced by the inconsistency of multichannel. The 7-bit input digital data is weighted to 16-bit in FPGA before fed into EDAC. Driven by a divided clock from a pulse pattern generator (PPG, Anritsu MU181020A), the electronic part works at a speed of about 1.042 GS/s.

The PPG is used to generate the sampling pulse train with a time jitter among hundreds of femtoseconds as shown in Fig. 2(a), where the pulse has a full width at half maximum (FWHM) of about 80 ps and a repetition rate of about 1.042 GHz. Eight custom-built DMLs are controlled by the output of EDACs, and the wavelengths are set to 1543.72 nm, 1544.52 nm, 1545.32 nm, 1546.12 nm, 1546.92 nm, 1547.72 nm, 1548.52 nm and 1549.32 nm respectively. By adjusting the index of electronic amplifier and the bias voltage of DML, the output optical power of each DML is about 0 dBm when digital data is all ‘0’ and is about 12 dBm when digital data is all ‘1’ respectively. The output of eight DMLs are combined in a WDM followed.

After that, the multi-wavelength mixed signal is fed into an MZM. The MZM (Oclaro Powerbit SD-20) driven by sampling pulse train works as an optical switch. The sampling pulse train is electronically amplified to match the half wave voltage of the MZM. A tunable optical delay line is used to adjust the temporal sampling position. After sampling by modulation, a multi-wavelength pulse train, which carries intensity information of eight analog signals in the same time window, is obtained. Then, in 982.6-meter commercial DCF with a dispersion coefficient of −152.66 ps/(nm.km), the different wavelength components of multi-wavelength pulse train are temporally separated. The whole chromatic dispersion is about 120 ps. A piezoelectric ceramic is used to adjust fiber length finely, the chromatic dispersion error can be controlled within tens of femtoseconds. The pulse train after dispersion medium is shown in Fig. 2(b), which is corresponding to a repetition rate of 8.33 GS/s. A 10 GHz bandwidth PD is used to convert the optical pulse train to electronic counterpart. The bandwidth of EDACs is about 1 GHz, and the bandwidth of all used optical devices is larger than 10 GHz. So, the bandwidth of the established experiment system is about 8 GHz.

A low pass filter is applied to obtain a smooth analog signal. With designed digital data stream as input, specific analog signal can be realized. Several kinds of waveform are generated with this ODAC system. We use four groups of digital codes to describe one signal period, which is corresponding to an analog signal frequency, which is of about 260.4 MHz. A signal period of sine wave outlined by a set of 32 pulses is shown in Fig. 3(a), and the result after a low pass filter with a bandwidth of 2 GHz is shown in Fig. 3(b). The spectrum of the filtered sine signal is measured by a spectrum analyzer (Anritsu MS2725C) to calculate the effective number of bits (ENOB) in Fig. 3 (c). The ENOB is a key indicator to reveal the practical capacity of system [20]. It can be derived from SINAD according to the empirical formula as Eq. (2):

$$ENOB = \frac{SINAD[\mathrm{dB}] - 1.76}{6.02} \tag{2}$$