XVI IMEKO World Congress
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Vienna, AUSTRIA, 2000, September 25-28

Optical analog-to-digital conversion, the state of the art

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Abstract: *The conversion rate of purely electronic analog-to-digital converters is limited in speed to conversion rates of some Gsps. A way to obtain substantially higher conversion rates is the use of photonic circuits as input stage of an analog-to-digital converter. A comparison of different approaches for optical analog-to-digital conversion is given with special emphasis on the properties of the key optoelectronic components employed in the different concepts. In particular we report the state of the art of the development of optoelectronic modulators, Self-Electrooptic-Effect-Devices and photodiodes and discuss the limitations imposed by the device properties to the conversion schemes.*
Keywords: Optical A/D conversion, electrooptic modulator, SEED.

1 INTRODUCTION

The main limitation for a large number of communication, image processing and radar applications is nowadays the speed of the employed analog-to-digital converters. In Fig.1 the relation between the conversion speed as a function of the Bit number for commercial electronical high-speed A/D-converters from four different manufacturers is shown. As indicated by the straight line an exponential relation of the type:

$$CS = 7.3 * 10^5 * e^{(-0.77*BN)} \quad (1)$$

holds for the conversion speed range between 1Msps and 1.5Gsps for A/D converters with resolutions between 8Bit and 16Bit, where CS is the maximum conversion speed at a given converter resolution in Msps and BN the number of Bits of the converter.

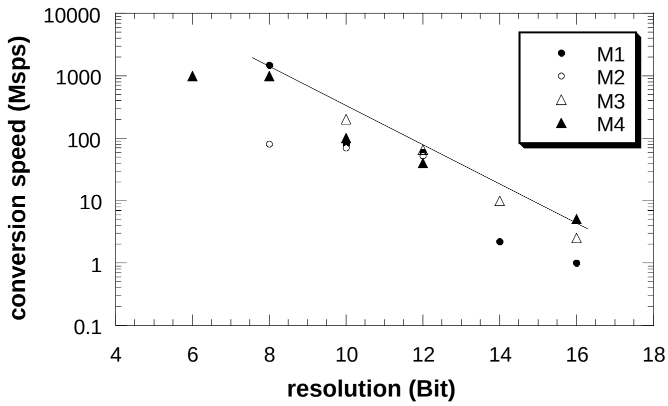

Fig.1 Conversion speed of commercial A/D-converters as a function of the converter resolution

A possible way out of this conversion bottleneck is the use of photonic techniques. Here we want to compare different photonic approaches, that have been used for the enhancement of the conversion speed and in particular give an overview over the state of the art regarding the development for the key optoelectronic components.

2 CONCEPTS FOR OPTICAL ANALOG-TO-DIGITAL CONVERSION

Most concepts proposed for analog-to-digital converters that use optical or optoelectronic techniques can be classified into two categories: The first category works with a photonic signal frequency down-converter as input stage followed by a conventional high speed electronic A/D-converter. In this category belongs for example the photonic time stretch A/D-converters [1, 2] that transform an ultra-high-speed optical signal into a series of parallel optical signals with lower frequencies. These type of photonic converters need at the input a fast electrooptic modulator as electrical-to-optical signal converter and a relatively slow photodiode at the output for interfacing the photonic down-converter to the subsequent purely electronic flash converter.

A second group of photonic A/D-converter schemes uses optoelectronic components in the analog-to-digital conversion process itsself. In particular Self-Electrooptic Effect Devices (SEEDs) [4] and optoelectronic thyristor [5] based smart-pixels are proposed to function as comparators in photonic A/D-converters. Also the Mach-Zehnder (MZ) interferometer based optical folding-flash A/D converter [6] belongs to this latter category of converters.

In the following we will describe the above mentioned concepts more in detail, discuss their speed limitations and identify the critical optoelectronic components.

2.1 Photonic time stretch converter

This type of converter consists of an ultra-short optical pulse generator, generally realized by using an erbium-doped fiber laser. The optical pulse is dispersed, for example in a some km long optical fiber, and the obtained chirped optical pulse is then intensity modulated using the ultra-fast electrical signal to be converted as control voltage of an electrooptic modulator. After sending the obtained optical signal again over an optical fiber with dispersion the now time stretched optical signal is converted to an electrical signal by a photodiode receiver and fed to the input of the subsequent electronic analog-to-digital converter. The effective input bandwidth of the A/D-converter in this system is increased by a stretch factor (M). A drawback of this scheme, however, is the need for difficult to realize high speed electrical switches in order to segment and interleave the analog input signal in M parallel channels before time-stretching in order to allow for the conversion of continuous time signals [2].
An interesting variation of the above described time-stretching scheme consists in the use of a wavelength division multiplexing element, like an optical grating, after the modulator instead of the second dispersive element. In this way the electrical input switch, that is rather difficult to realize because of high frequency requirements, can be eliminated. Each output of the Wavelength Division Multiplexer (WDM) samples a part of the optical spectrum and each part of the spectrum corresponds to a different time range of the analog input signal[1, 2]. This configuration is shown in Fig.2.

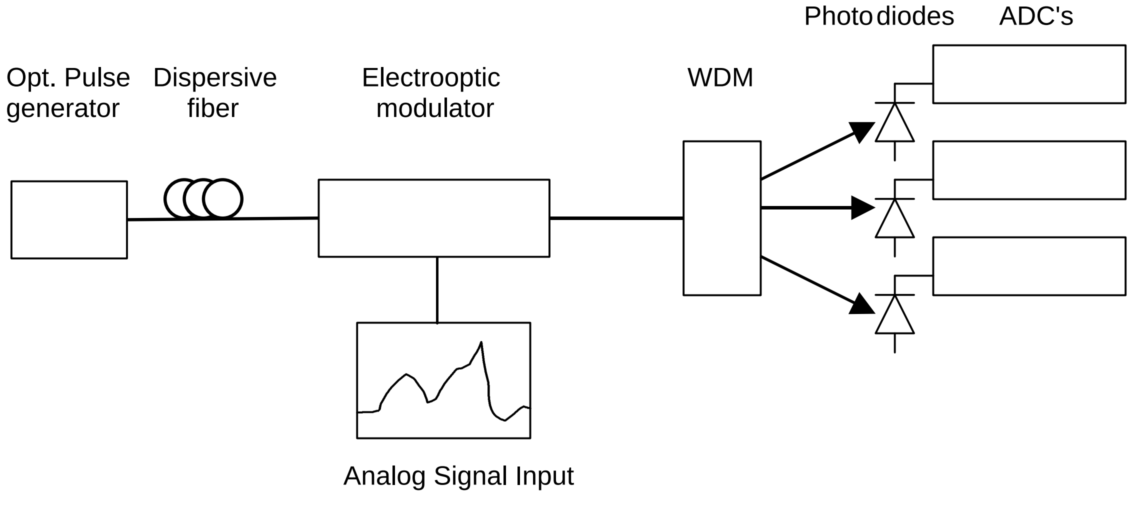

Fig.2 Schematics of a time stretch photonic A/D-converter with Wavelength Division Multiplexer (WDM)

Regarding the possible speed of photonic time stretch systems input bandwidth up to 50GHz have been predicted and for an WDM based system conversion speeds up to 10Gsps have been already obtained [2]. The limiting optoelectronic elements are mainly the electrooptic modulators and the wavelength division multiplexing device when using the latter mentioned approach. It should be noted that for fiber-optic data transmission integrated optical gratings with more than 30 output channels have already been realized [7].

2.2 Self-Electrooptic Effect Device based All-Optical A/D-conversion

The All-Optical Analog-to-Digital Converter (OADC) based on the Self-Electrooptic Effect Device is intended for applications where the digital output signal is required to be an optical signal itsself. Of course with the use of a frontend fast electrooptic modulator and photodiode output O/E converters also electrical analog-to-digital conversion can be performed.

SEEDs are basically reverse biased electrooptic modulators, that use a positive feedback via the induced photocurrent in order to obtain a negative differential resistance region in the current-voltage characteristics under illumination. Different SEED types can be distinguished for example by the different electrical load configuration or by the structure of the active intrinsic region. Most common are SEEDs with Multi-Quantum-Well intrinsic active modulation layer, where the modulation is based on the Quantum-Confined-Stark-Effect [8,9] or with superlattice intrinsic layer, where the Wannier-Stark effect is exploited [10,11]. The simplest load configuration - the R-SEED - consists of a pin-diode type electrooptic modulator where the reverse bias has been applied through an external resistor. In Fig.3 the scheme of a R-SEED with InP/InGaAs superlattice intrinsic layer and and in Fig.4 the resulting optical transfer function for different electrical biasing conditions are shown. One observes a wide open hysteresis for example at a wavelength of 1550nm, with -45V applied bias through a 4M resistor. This can be exploited for example for the realization of an optical memory. Changing the biasing conditions slightly (-25V, 2M), we observe threshold operation without hysteresis. It should be mentioned that the SEED - despite the use of an internal electrical biasing circuit - is an all optical nonlinear device. It has been shown that by changing the electrical bias conditions (R, V_{bias}) and the wavelength of the incident light, a large variety of different optical transfer functions can be realized [12].

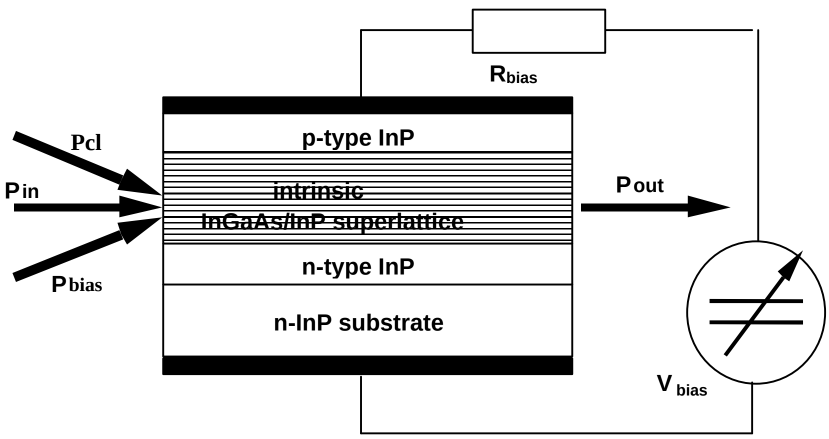

Fig.3 Schematics of an R-SEED realized with a InGaAs/InP based Wannier-Stark electrooptic modulator

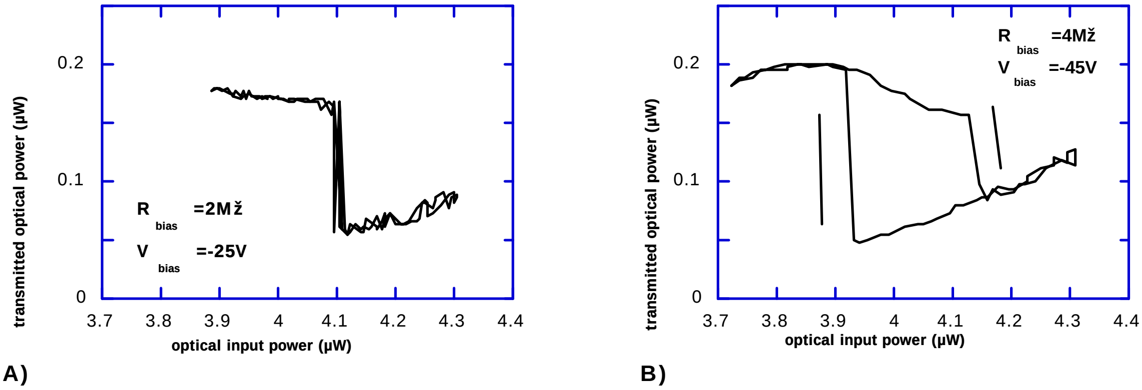

Fig.4 Optical transfer functions for TE-polarized light at 1550nm of a Wannier-Stark effect based R-SEED under different biasing conditions A) V_{bias}=-25V and R_{bias} = 2M and B) V_{bias}=-45V and R_{bias}=4M

The OADC scheme that has been proposed in literature [4] uses the symmetric SEED (S-SEED) configuration, where two modulators are connected in the way, that one pin-diode is working as the electrical load of the other one, without inserted resistors. The SEED acts as an optical comparator and the operation of a 2-bit binary encoder has been demonstrated. Most critical is the complexity of the required microoptic setup and the stability of the optical biasing. An evaluation of the conversion speed gave a minimum sampling period of 953ps. It has also been shown, that the sampling period in this case was not limited by the switching time of the used all-optical quantizers. Switching speeds of S-SEEDs of about 33ps, well below the above mentioned minimum sampling period, have been already reported [13]. They are basically limited by the S-SEED time constant and the vertical carrier mobility [4]. In the case of the R-SEED the switching time is limited by the RC constant given by the values of the external resistor and the modulator pin-diode capacitance.

2.3 Optical folding-flash analog-to-digital converter

Another approach for a photonic analog-to-digital converter is based on the similarity of the electro-optical transfer function of a Mach-Zehnder (MZ) interferometer type modulator with the Gray-code digital data rappresentation. The original design [14] required an array of only N MZ-modulators for the construction of an all optical analog-to-digital converter with N Bits. A drawback, however, was the limited resolution of the converter, because the the relation between the number of N and the full scale analog input voltage (V_{fs}) is given by the following equation

$$V_p = (1/2^N) * V_{fs} \qquad (2)$$

Where V_π is the half-wave voltage, necessary to drive the Mach-Zehnder modulator between the transmission minimum and maximum. This means that even a 4 Bit ADC is difficult to obtain, because - following Eq.(2) - it would require a V_π voltage of 0.63V, far below the obtained values for example for $LiNbO_3$ based Mach-Zehnder electrooptic modulators [15]. This restriction has been lowered by the use of a modified conversion scheme, based on analog encoding, that is shown in Fig.5 for a 4 Bit A/D-converter.

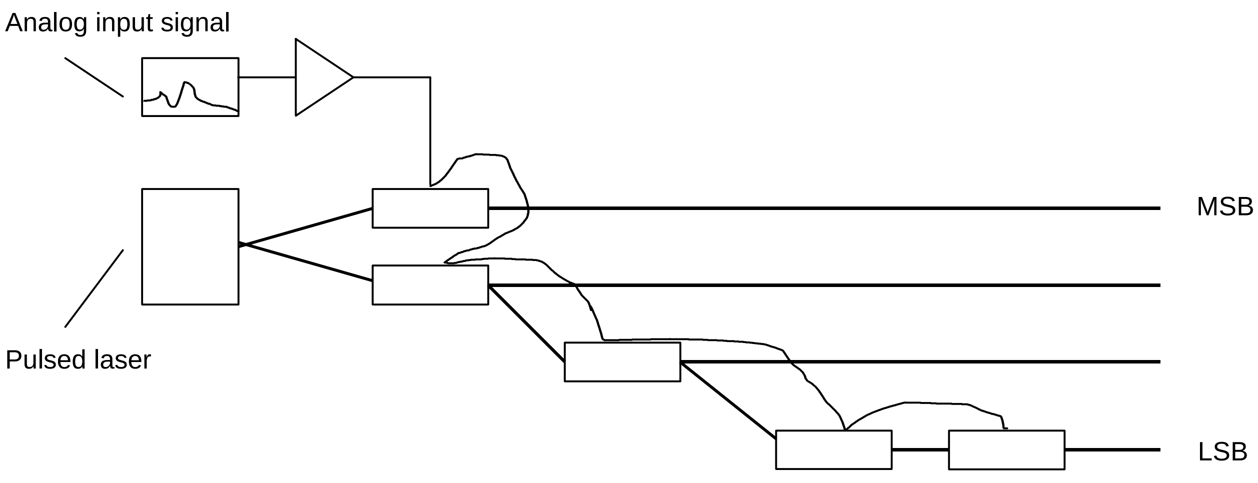

Fig.5 Optical folding-flash analog-to-digital converter with five Mach-Zehnder modulators

In this case the needed V_π voltage for a 4 Bit converter is $V_{fs}/2$. This means that for an analog input range of 10V a half-wave voltage as high as 5V would be sufficient. This is a value that has been already obtained in commercial 10Gbps fast $LiNbO_3$ based Mach-Zehnder electrooptic modulators [15]. It has to be mentioned that for the latter conversion scheme fast photodetectors, transimpedance amplifiers and electronic latched comparators are required. Converters up to 6 Bit are practical and an enhancement of conversion speed in comparison to purely electronic folding-flash converters can be expected, because in the latter case the bandwidth of the converter is limited by the speed of the electronic folding block. As already mentioned does the optical folding-flash analog-to-digital converter not require any encoding circuitry, because the digital output signals are already in the Gray-code format. For a 4 Bit A/D-converter only 5 MZ-modulators are used. That means that this configuration is not much more complex than the original approach by Taylor [14].

2.4 Optoelectronic thyristor based photonic smart comparator

Another concept based on a photonic comparator approach is the optoelectronic thyristor based analog-to-digital converter. The optoelectronic thyristor is a three terminal device with a sharp electrical switching characteristics that acts as an optical emitter above switching threshold [5]. It has been proposed to be integrated into a classical electronic comparator configuration with the advantage of an inherent optical output that enables to transmit the digital output result from the comparator at high speed via optical fiber to a remote digital logic circuit for further processing. In this way a high speed A/D-converter can be designed where the comparator function is put in a remote location as compared to the rest of the electronic circuitry. Typical thyristor switching voltages of about 6V, a holding current of 5mA and a laser threshold current of 55mA have been achieved.

3 STATE OF THE ART OF SOME KEY OPTOELECTRONIC COMPONENTS FOR PHOTONIC A/D-CONVERSION

As we have seen there are a large number of different optical and optoelectronic components used for photonic A/D-converter realizations. For example in the photonic time stretch converter we have the erbium doped fiber laser, the electrooptic modulator, an arrayed waveguide grating (AWG) and finally the photodetectors as key components. In the case of the optical folding-flash converter, Mach-Zehnder interferometer modulators, a pulse laser and fast photodiodes are required. The SEED based all optical A/D-converter needs besides the S-SEED array also laser diodes for the optical biasing of the comparators, optical gratings for spatial addressing of the SEEDs and a variety of microoptical elements. Here we limit the discussion to the properties of three active optoelectronic components: photodiodes, modulators and Self-Electrooptic-Effect Devices.

3.1 Receiver diodes

Most schemes using optical input stages in order to enhance the speed of electronic analog-to-digital converters need finally a photoreceiver diode in order to reconvert the processed optical signal into an electrical signal prior to the final purely electrical analog-to-digital conversion. The required bandwidth of the receiver diode is in the order of few GHz, which is not critical as compared to the nowadays obtained bandwidths above 40GHz as achieved as well by p-i-n photodiodes as by Metal-Semiconductor-Metal (MSM) photoreceivers. For example a monolithic InGaAs-InP p-i-n-/HBT receiver module exhibiting pulse risetimes of 9ps [16], a MSM photodetector with a bandwidth of 70GHz [17] and a 20Gbit/s datarate for a avalanche photodiode receiver [18] have been reported. A strictly linear relationship between the incident optical power and the resulting photocurrent in general is obtained for a large range of optical input powers. Detector speed is more critical for the photodiodes used for the evaluation of the photonic A/D-converter quality rather than for the photodiodes used in the converter itsself.

3.2 Electrooptic modulators

Three main requirements have to be fulfilled by the electrooptic modulators to be used for photonic analog-to-digital converters. They should work at very high speed, require low driving voltages and often also a linear electrooptic transfer function is important for analog operation. In general the response time of electrooptic modulators is limited by the parasitics of the devices. Nowadays this limit can be overcome by the use of advanced modulator designs like the travelling-wave concept [19]. But also for traditional pin-diode modulators bandwidths exceeding 40GHz have been reported [20,21]. Another important property for modulators used for A/D-converters is the needed driving voltage for a given optical contrast. The voltage should be in a range comparable to the usually specified input voltage range of an electronic A/D-converter in order to avoid the need for electronic input amplifiers with extremely high slew-rate. State of the art modulators fulfil this requirements with good optical transmission contrast at reverse bias voltages below 3V [11,22]. More critical, however, is the question of the linearity. In analog fiber-optic links - like for example analog TV distribution - today the light modulation is mostly done by direct laser diode modulation, that intrinsically shows a good linearity between laser current and emitted optical power. Electro-optical modulators in general do not show a linear relation between the applied bias voltage and the transmitted optical power [23]. As we have seen the non-linear behaviour is sometimes desirable - as in the case of the optical folding-flash analog-to-digital converter. In general, however, it might be necessary to correct for the modulator nonlinearity by subsequent electronic data processing.

3.3 Self-Electrooptic-Effect Devices

Since the above mentioned realization of a SEED based all optical A/D-converter [4], the technology of Self-Electrooptic-Effect Devices has made a lot of progress. The application of Logic SEEDs (L-SEEDs) [24] could for example simplify the optical implementation and replace part of the critical micro-optical elements and simplify the optical alignment. Also the optical power needed for the switching of the comparators has been reduced by new technologies [25]. It would therefore be interesting to check if a new SEED based all optical A/D-converter system could lead to reduced conversion times with sampling rates well above the former mentioned 1Gsps.

4 CONCLUSIONS

Different approaches of photonic analog-to-digital conversion schemes have been compared. In particular the photonic stretch converter has been shown to enhance significantly the conversion speed compared to purely electronic A/D-converters with moderate requirements in system complexity. The required key optoelectronic and optic components have been already developed for fiberoptic data transmission systems. Sampling rates exceeding 10Gsps with continuous signal conversion have been demonstrated, that potentially can be extended up to 50Gsps. The critical component in this configuration is the electrooptic modulator. The speed requirements of the employed photodiodes, used for the interfacing with the subsequent electronic, however, can be easily fulfilled by nowadays pin-diode, MSM- and APD photoreceivers.

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