

# A Programmable Monolithic InP Optical-CDMA Encoder/Decoder

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**Abstract:** We demonstrate a monolithically integrated InP optical-CDMA encoder/decoder chip encoding sub-picosecond pulses in the 1.55  $\mu\text{m}$  wavelength window using eight orthogonal Walsh codes. The chip consists of two 200 GHz AWGs and electro-optic phase modulators in InP/InGaAsP.

**Introduction:** Optical Code Division Multiplexing Access (O-CDMA) systems have the potential of providing very flexible access of high-network capacity to multiple end users [1]. While the feasibility of O-CDMA has been demonstrated in free space optical systems [2], an integrated photonic chip with the same functionalities would be required for large-scale deployment. The key element in an O-CDMA system is the spectral phase encoder/decoder (ED), for which AWGs are very attractive components due to their high spectral resolution. An AWG-based ED using Si technology and a non-programmable external phase modulator has been reported in [3]. This paper presents monolithic AWG-based ED in InP/InGaAsP. It incorporates a high-speed electro-optic phase modulator array for rapid programmability and negligible power consumption. The approach is suitable for future monolithic integration of the encoder and decoder in O-CDMA transmitters and receivers.

**Operation Principle and Design:** An O-CDMA encoder encodes a sub-picosecond pulse by slicing its spectrum into multiple spectral segments and by applying a phase shift of 0 to  $\pi$  radians to each individual spectral slice before recombining them again into a single pulse. This spectral encoding results in spreading of the pulse in the time domain across tens of picoseconds. At the receiver side, the short pulse can only be reconstructed by applying the conjugate code to the encoded pulse. The properly decoded short pulse can thus be easily distinguished from the undecoded broad pulse. Fig 1a shows the ED integrated chip layout. A sub-picosecond optical pulse enters AWG1 from one of the input waveguides. The multiple (five) inputs of the AWGs provide discrete tuning of the wavelength to ensure that the filter characteristics of the AWG pair in the encoder overlap. AWG1 spectrally decomposes the pulse into slices corresponding to AWG1's spectral transmission to its eight output channels. Each of the spectral slices is phase modulated separately in 1mm long electro-optic phase modulators. Equalizing delay lines shown in Fig 1a are to prevent relative time delays between the spectral slices in the absence of phase modulation. Finally, the eight slices are multiplexed by AWG2 and the combined optical pulse emits from one of the output waveguides. The two AWGs are identical by design. They have 8 channels with 200 GHz channel spacing, a central wavelength at 1546 nm and a free spectral range (FSR) of 2.4 THz. The total wavelength span covered by the 8 channels is 1.6 THz, which has enough spectral bandwidth to encode 300 fs wide pulses. The phase modulators are reverse biased  $p$ - $i$ - $n$  junctions, which consume negligible power ( $<1\text{mW}$ ) and have, in principle, a very short switching time (nanoseconds). The overall chip size is 10 mm x 4 mm.

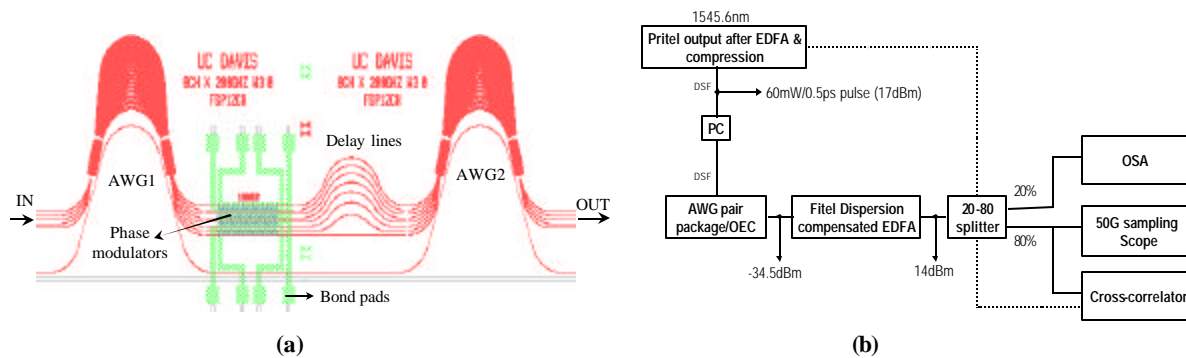


Figure 1a) O-CDMA encoder/decoder (ED) chip containing demultiplexer AWG1, an eight channel phase modulator array with bond pads, delay lines for optical path length equalization, and multiplexer AWG2. b) ED chip measurement set-up.

**Fabrication:** The O-CDMA chip was fabricated on an n-type InP substrate with a 1.5  $\mu\text{m}$  thick n-type InP buffer layer. The waveguiding layer above the cladding layer consists of quaternary material (1.15Q) with n-type doping of  $1\text{E}16\text{cm}^{-3}$ . The film was clad with a 2.2  $\mu\text{m}$  thick InP layer. On top of the InP p-type cladding is a 0.1  $\mu\text{m}$  thick InGaAs contact layer grown with a p-type doping of  $5\text{E}18\text{cm}^{-3}$ . The waveguides were fabricated by defining and patterning them using photolithography on a 270 nm thick PECVD SiO<sub>2</sub> etch mask followed by a CF<sub>4</sub>-O<sub>2</sub> reactive ion etch (RIE) process. The ridge waveguides were etched 50 nm into the quaternary waveguiding layer using a Chlorine-Hydrogen ECR process. The chip was planarized using a 2.4  $\mu\text{m}$  thick

bisbenzocyclobutene (BCB) polymer layer that was etched back uniformly until the top of the waveguide ridge was exposed. The remaining SiO<sub>2</sub> masking material was removed and a *p*-metal (Ti/Pt/Au) contact was evaporated in a liftoff process using bi-level resist. The backside of the wafer was then lapped to 200 μm and n-metal (AuGeNi/Au) deposited. The finished ED chip was packaged in a butterfly package with separate electrical connections to the individual phase modulator channels, pigtailed lensed fibers for coupling signal into and out of the chip, and a Peltier element and thermistor for temperature control.

**Results:** Fig.1b shows the experimental set-up for characterizing the ED chip. The mode-locked laser generated 0.4ps pulses with a repetition rate of 10 GHz that were passed through a polarization controller (PC) before being fed into the ED chip input. The ED chip output was amplified by a dispersion compensated EDFA and fed in either a cross-correlator or a 50GHz sampling scope for time domain characterization. A 20/80 power splitter was used to monitor the optical spectrum of the signal on an OSA. The cross-correlator traces from the ED chip output are displayed in Fig.2a for Walsh codes W6=[10101010] and in Fig.2c for W8=[10010110], where the numbers “0” and “1” ideally should correspond to a phase shift of 0 and π radians respectively. In the actual measurement these numbers corresponded to 0V and 14V reverse bias. The trace for 0V across all phase modulator channels shows three large peaks instead of the expected single peak corresponding to the unencoded short pulse, suggesting that spectral shape of optical losses and some initial code offset in the modulator arms due to optical paths length errors possibly due to processing tolerances. The dominant 1 ps wide pulse observed for the W6 code at 14V indicates that for this code the code offset was almost completely compensated. This is shown in the simulations (dotted line) in Fig. 2b, which show the cross-correlator output for  $0.65\pi \cdot W6$  (corresponding to 0V) and  $0.4\pi \cdot W6$  codes. From Fig. 2d it can be seen that the W8 code simulation, with  $-0.65\pi \cdot W6$  offset correction, is in agreement with the measurement. The additional peaks in the measurement with respect to the simulations are due to some mismatch between the pass-band transmission characteristics of the AWG pairs, causing the ED transmission spectrum to develop fine splitting sub peaks, which translates into additional peaks in the time domain measurements. In conclusion, we have realized an O-CDMA encoder in InP/InGaAsP and demonstrated encoding of sub-picosecond pulses.

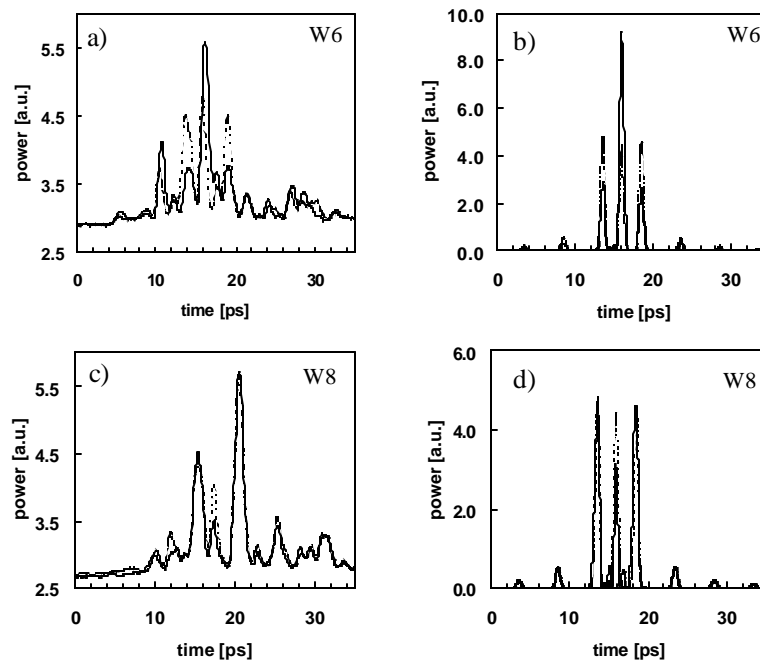


Figure 2. Encoder/decoder chip output for Walsh code W6 in 2a (experiment) and 2b (simul.), and for W8 in 2c (experiment) and 2d (simul.). The dotted lines correspond to 0V on all phase modulators, the solid lines to 14V or 0V according to the code.

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