

Integrated parallel spectral OCDMA en/decoder

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Integrated Parallel Spectral OCDMA En/Decoder

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Abstract—In this letter, a passive integrated device is presented that enables cost-effective parallel encoding and decoding in a spectral amplitude encoded optical code-division multiple-access transmission system. The device is monolithically integrated in InP–InGaAsP. Simulation and experimental results are given.

Index Terms—Code-division multiaccess, optical components, optical fiber communication, parallel processing, passive circuits.

I. INTRODUCTION

OPTICAL code-division multiple-access (OCDMA) has gained serious interest by researchers worldwide [1], [2]. Attractive features of an OCDMA transmission system are high resilience against eavesdropping and interference. Inherently it is a very secure technique of transmitting data. As research matures, multiple-access by code increasingly becomes a third option next to time and wavelength. One of the applications of OCDMA is optical communication on passive optical networks (PONs). OCDMA has a powerful natural fit on PON because both are based on broadcast-and-select. As such, optimal sharing of optical medium and carrier is obtained. A PON shared-fiber architecture is envisaged to provide optical transparency in the access network layer, or even beyond [3]. Using OCDMA on multiple wavelength channels in a PON offers huge bandwidths to a large number of subscribers for reduced infrastructure costs. The integration of optics herein is key for large-scale mass production and deployment.

Many flavors exist in OCDMA which are generally distinguished by source (coherent/incoherent) and domain (time/frequency) [4]. In most coherent systems, short pulses are used which require expensive sources. We consider incoherent spectral amplitude encoded (SAE) OCDMA employing broadband sources and bipolar signaling. Incoherent sources such as light-emitting diodes (LEDs) are cost-effective. Bipolar signaling has a 3-dB signal-to-noise ratio advantage over unipolar signaling [5] and is required to achieve full rejection of multiple user interference (MUI) [6]. In this case, two complementary fringe patterns are used to represent both the user and the data on the network which limits the receiver bandwidth to the data rate thereby offering additional cost efficiency. This kind of modulation is denoted as spectral shift

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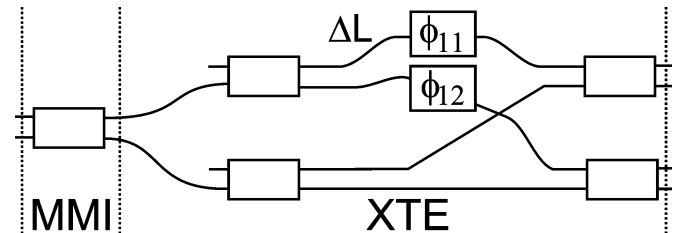


Fig. 1. Schematic of one-stage parallel spectral E/D.

keying (SSK). A bipolar SAE OCDMA transmitter may use SSK. A bipolar receiver is constructed by a decoder with balanced detection. The use of a bipolar transmitter enhances the use of the bipolar receiver [7]. An integrated Mach–Zehnder interferometer (MZI)-based bipolar transmitter is considered here. It was previously used on a point-to-point transmission link [8]. Point-to-multipoint communication is made in a PON between an optical line termination (OLT) and multiple optical networking units (ONUs). Parallel processing of upstream and downstream data is required at the OLT to allow truly asynchronous medium access. In this letter, for the first time a single passive integrated device is presented that has parallel (de)coding functionality. Its cost-efficient design only uses a single optical source to simultaneously generate or process a multitude of encoded optical spectra.¹ The processing power, expressed in the number of phase codes it generates/processes, can be easily increased because of the modular construction.

First, the operation principle and model of the device and basic building block are presented in Section II. The integration in InP–InGaAsP is depicted in Section III and results on simulation and experiment are discussed in Section IV. Finally, Section V concludes the letter.

II. PARALLEL SPECTRAL ENCODER AND DECODER

Truly asynchronous OCDMA in a PON requires an OLT with the capability to simultaneously communicate with all ONUs. Equipping the OLT with as many en/decoders (E/Ds) as ONUs is not the most efficient way. A significant reduction in cost and hardware complexity is achieved when a single device is used. We have designed such a parallel spectral E/D (or tree). A tree E/D can be combined with cascade E/Ds [8] at the ONUs. It is modularly constructed by a 2×2 3-dB multimode interference (MMI) coupler and a 2×4 building block referred to as crossed tree element (XTE) as shown in Fig. 1. One simply connects XTEs to the outputs of the one-stage tree for a two-stage tree and continues to do so until N stages. The only requirement is

¹Eindhoven Univ. of Tech., Netherlands Patent Application 1031833, May 17, 2006.

that all path length differences are multiples of ΔL , the path length difference of the first stage. By launching optical power in one of the inputs, the tree generates 2^N sets of complementary fringe patterns.

The transmission characteristics are described according to the propagation matrix [9]. An exact 3-dB coupling ratio is assumed for all couplers in Fig. 1. Accordingly, the propagation matrix \mathbf{M}_{T1} of a one-stage tree is expressed as follows:

$$\begin{aligned} \mathbf{M}_{T1} &= \mathbf{M}_{XTE} \cdot \mathbf{M}_{MMI} \\ &= \frac{1}{2} \begin{bmatrix} jh_\varphi(\phi_{11}) & -1 \\ -h_\varphi(\phi_{11}) & j \\ h_\varphi(\phi_{12}) & j \\ jh_\varphi(\phi_{12}) & 1 \end{bmatrix} \cdot \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \end{aligned} \quad (1)$$

with $h_\varphi(\phi_{mn}) = e^{-j(\varphi+\phi_{mn})}$, ϕ_{mn} the value of the phase shifter mn , $\varphi = 2\pi f \cdot n_{\text{eff}} \cdot \Delta L/c$, f the optical frequency, n_{eff} the effective refractive index of the waveguide, ΔL the path length difference, c the speed of light, and j the imaginary unit. The path length differences and phase shifters can be randomly positioned in the XTE. The only requirement is that a delayed and nondelayed optical field interfere at the final coupler. The crossover between the upper and lower branch of the XTE is mandatory to maintain the spectral width of the fringe patterns at the outputs of the tree. Without crossover, the XTE contains two individual MZIs. Such a building block can be used to construct a multi/demultiplexer and is, therefore, referred to as multi/demultiplexer element (MDE). The propagation matrix \mathbf{M}_{MDE} is as follows:

$$\mathbf{M}_{MDE} = \frac{1}{2} \begin{bmatrix} jh_\varphi(\phi_{11}) + j & 0 \\ -h_\varphi(\phi_{11}) + 1 & 0 \\ 0 & jh_\varphi(\phi_{12}) + j \\ 0 & -h_\varphi(\phi_{12}) + 1 \end{bmatrix}. \quad (2)$$

As shown, the MDE modifies the input fields independently, which is not the case for the XTE. This leads to an important difference between MDE and XTE if the injected optical power is not uniformly distributed over a particular spectral range, e.g., one free spectral range (FSR) period. That situation occurs when a set of complementary spectra is injected. Crossing over the waveguides of the two arms in the XTE recovers optical components which are filtered or attenuated in the MDE. Cascading MDEs results in narrow filtering around parts of the original spectrum. Cascading XTEs results in fringe patterns at the outputs which remain to have the spectral width of the input signal. Thus, if no interference history is present at the input, the MDE and XTE give a similar response. The first stage of an N -stage tree can be either of both.

A careful consideration of (1) shows that a one-stage tree only generates two orthogonal sets of complementary spectra. This situation is met for $\phi_{11} = 0$ and $\phi_{12} = \pi/2$, or vice versa. The orthogonal sets of complementary spectra are denoted as phase codes. The phase codes are binary identified according to the setting of the phase shifter at each stage, i.e., a 0 or 1 is appointed to a phase shifter with value 0 or $\pi/2$. The resulting binary word is then referred to as a phase code identifier (PCI). A one-stage tree, therefore, has the PCIs 0 and 1.

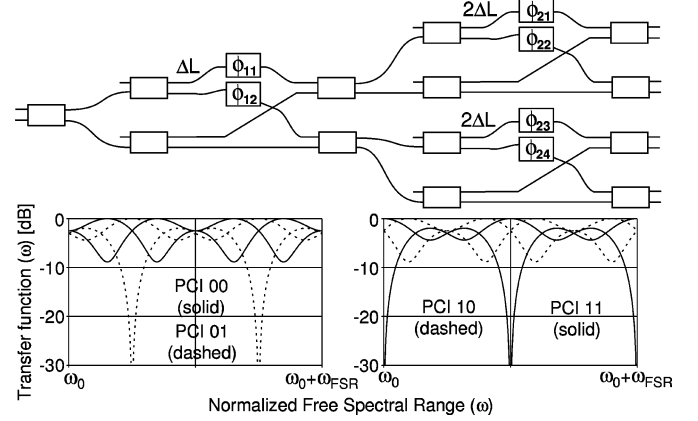


Fig. 2. Schematic and phase codes of two-stage parallel spectral E/D.

TABLE I
WAFER LAYER STRUCTURE USED FOR INTEGRATION OF TREE

Material	d [nm]
p-InGaAs	100
p-InP	1200
i-InP	300
Q(1.25)	500
n-InP	4000
n-InP	sub

A detailed study on the orthogonality between phase codes has been done by [10]. Two factors determine the orthogonality, namely the PCIs and the multiplication factors applied at each stage to the path length difference of the first stage. A two-stage tree has a multiplication factor of two in the second stage. The values of the phase shifters should be $\phi_{11} = 0$, $\phi_{12} = \pi/2$, $\phi_{21} = 0$, $\phi_{22} = \pi/2$, $\phi_{23} = 0$, and $\phi_{24} = \pi/2$ such that the PCIs are 00, 01, 10, and 11. The architecture of a two-stage tree is shown in Fig. 2 with the phase codes plotted for a normalized FSR. The phase codes correspond with the ones shown in [10]. An analysis in [11] confirms that tree and cascade E/Ds generate the same phase codes. However, a coupling loss of 3 dB per stage and an extra phase shift per branch are introduced.

III. INTEGRATION IN InP–InGaAsP

The one-stage tree is monolithically integrated in InP–InGaAsP material. The device is fabricated on a layer structure as shown in Table I.

In this layer stack, two waveguide layers are present; the primary waveguide layer is a 500-nm undoped InGaAsP layer with a bandgap of 1.25 μm , and the secondary waveguide layer is a 4- μm -thick lowly N-doped InP layer. The passive waveguides, the MMI couplers, and the electrooptical phase shifters are ridge structures, shallowly etched, 100 nm into the Q(1.25) layer. A spot size converter (SSC) is made at the output by tapering the 3- μm -wide waveguides both laterally and vertically down to the secondary waveguide layer, in which an 11- μm -wide fiber matched waveguide is etched to couple the light efficiently to a standard fiber [12]. The measured insertion loss is around 10 dB. This accounts for less than 2-dB propagation losses (2.5 dB/cm), 1.5-dB MMI losses, 2 \times 3 dB splitting losses at the XTE and

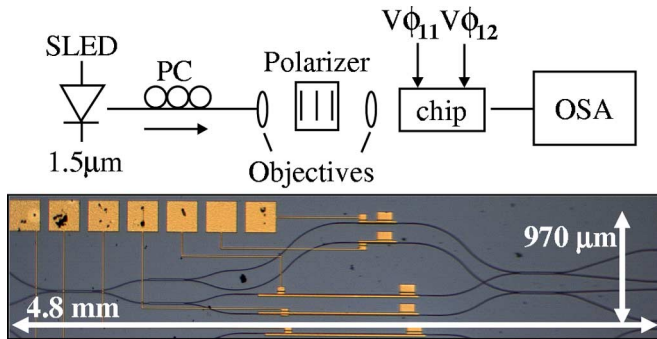


Fig. 3. Measurement setup and picture of integrated one-stage tree.

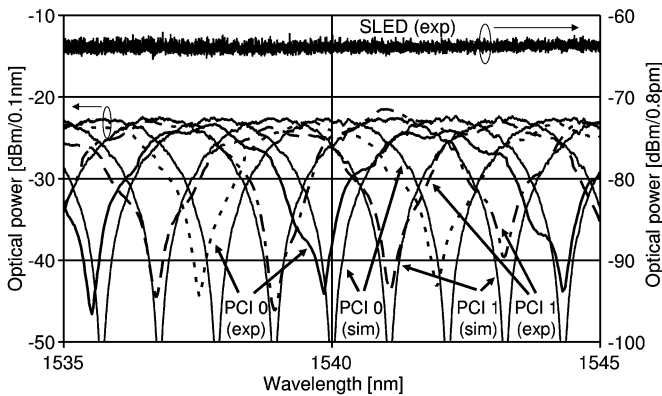


Fig. 4. Measured and simulated phase codes of one-stage tree.

output, and a 1.5-dB SSC loss. The XTE itself has about 5-dB insertion losses. We also measured an alignment tolerance of $\pm 1.5 \mu\text{m}$ for 1-dB excess loss at the SSC.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The phase codes of a one-stage parallel spectral E/D are evaluated by simulation. The optical input spectrum has to be as flat as possible to minimize its effect on the spectral shape of the phase code. All elements of the E/Ds are simulated ideal, i.e., with no additional noise sources. The frequency response of the one-stage tree is measured by using a superluminescent LED (SLED). Fig. 3 also shows a picture of an actual one-stage tree. Driven with a 500-mA bias current, the SLED produces around 12 dBm of optical power at a spectral width of 80-nm full-width at half-maximum. The polarization is set to TE-mode via a polarization controller (PC) and a free-space polarizer for the strongest electrooptic efficiency in the phase shifters, mainly caused by the strong polarization dependency of the Pockels effect. The E/D is designed for a large FSR of 5 nm to reduce speckle noise during a transmission. The center wavelength is at $\lambda_0 = 1540 \text{ nm}$, where the SLED has its flattest response. Measured and simulated spectra are shown in Fig. 4. All phase codes are generated simultaneously. First, phase shifters ϕ_{11} and ϕ_{12} are both used to tune the spectra to λ_0 , where ϕ_{12} is set to $\pi/2$. The slight difference around 1540 nm between measurements and simulations is merely caused by a tuning error

of ϕ_{11} . The periodicity of the MZI is clearly observed with an FSR of 4.3 nm. The error of 0.7 nm corresponds to an extra path length of $22 \mu\text{m}$ mainly due to the various margins in the production process. The evenly distributed optical power measured per output indicates that all MMI couplers have a coupling ratio around 3 dB. It also assures that balanced detection can be used. The ripple in the spectra corresponds with an identified resonance cavity on chip. An improved design should reduce this ripple. Transmission experiments and MUI/orthogonality measurements could not be done due to insufficient resources.

V. CONCLUSION

We have discussed a parallel spectral E/D to be used in an SAE OCDMA transmission system, e.g., on a PON. The proof of principle is shown by the measured frequency response of a one-stage tree which has been monolithically integrated in InP-InGaAsP material.

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