

# Multi-Stage En/Decoders Integrated in Low Loss $\text{Si}_3\text{N}_4\text{-SiO}_2$ for Incoherent Spectral Amplitude OCDMA on PON

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*In this paper, we show and analyze, for the first time, the static performance of integrated multi-stage cascade and tree spectral amplitude OCDMA en/decoders (E/Ds) which are fabricated in the low loss  $\text{Si}_3\text{N}_4\text{-SiO}_2$  material system. Combined with incoherent broad spectral sources these E/Ds enable cost-effective node deployment in an OCDMA passive optical network architecture. We discuss the design of a crucial component, namely the 2x2 3dB multi-mode interference (MMI) coupler. Finally we show measured spectral codes of two-stage E/Ds and compare these with modeled ones.*

## Introduction

The current deployment of fiber-optic access networks stimulates the research towards cost-reducing solutions. Photonic integration of optical functions, passive technologies, resource sharing and centralized network management are key issues to be addressed. Optical code division multiple access (OCDMA) on a passive optical network (PON) is considered to be an attractive, cost-effective and complementary technology which, for example, increases the number of users per spectral unit [1]. We propose to use the integrated, incoherent spectral amplitude encoded (SAE) OCDMA technique in order to further reduce deployment costs. The en/decoders (E/Ds) used are Mach-Zehnder Interferometer (MZI) based cascade and tree structures which are passive, tunable and periodic [2]. They filter the broad spectral input of an incoherent source, for example a superluminescent light emitting diode (SLED). The filter pattern and its complementary constitute the spectral code and are both used in binary data transmission (spectral shift keying). We have successfully demonstrated a one-stage tree E/D in InP-InGaAsP [3]. However in this paper, we present E/Ds integrated the  $\text{Si}_3\text{N}_4\text{-SiO}_2$  material system because of the low propagation losses and CMOS-compatible production process [4]. The mask design and actual devices are shown here, for the first time. The parameters of critical components are discussed in detail. We show high-quality optical characteristics for two-stage E/Ds. We report an excellent match with the design and the analytical model.

The rest of the paper is organized as follows. Section 2 describes the E/D design and experimental setup to characterize the chips. Then, Section 3 shows, in detail, the design of a 2x2 3dB MMI coupler. Then, Section 4 reports on the optical characteristics of two-stage cascade and tree E/Ds. Finally, Section 5 concludes the paper.

## Design and experimental setup

The E/Ds are designed for a center wavelength of 1550nm where the fabrication process is well-defined. Optical wave guiding is achieved via a thin  $\text{Si}_3\text{N}_4$  stripe (core) which is

surrounded by a thick SiO<sub>2</sub> cladding layer on top of a silicon substrate and a 4μm SiO<sub>2</sub> buffer layer. This causes a polarization dependency of the chips. The TriPLeX technology [4] has been further developed to remove that restriction but this has not been applied here. The waveguides are 2μm wide and 145nm high, giving an  $n_{\text{eff}}=1.54$  for TE@1550nm and single mode operation. The E/Ds can be tuned by phase shifters consisting of a 10μm wide heater on top of the waveguide. A phase shifter is placed in all E/D arms for a red or blue shift of the spectrum. All heater leads are connected to probe pads at a pitch of 250μm. We have designed spot size converters (SSCs) in order to reduce the overlap losses at the fiber-chip interface. The waveguide is horizontally and vertically tapered to a width of 1.5μm and a height of 70nm to match the spot size of a standard single mode fiber (SSMF) with less than 1dB overlap loss. The in- and outputs are at a pitch of 250μm to match fiber-arrays. All E/Ds are modularly constructed as discussed in [2]. The E/D path length differences are calculated for a free spectral range (FSR, or: periodicity) of 5nm because a broad spectral code reduces speckle noise during fiber transmission [5]. The experimental setup is shown in Fig. 1. An SLED is driven with 500mA for a 12.1dBm optical field with an 87.5nm full-width at half-maximum around 1535nm. An isolator is added to block any back-reflections. We optimize the received optical power for TE-mode via the polarization controller (PC). The red Fabry-Perot (FP) laser is used to ease the chip alignment since the Si<sub>3</sub>N<sub>4</sub>-SiO<sub>2</sub> material system is transparent for visible light. We placed cleaved SSMFs at the input and output of the chip due to the unavailability of anti-reflection coated fibers. The optical field is measured using either a power meter or an optical spectrum analyzer (OSA) with a resolution of 0.05nm.

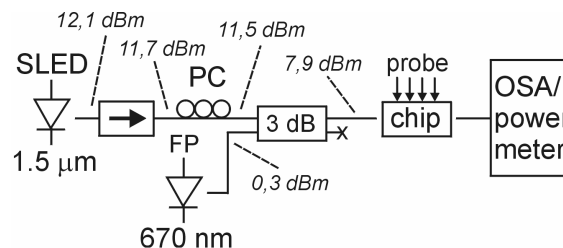
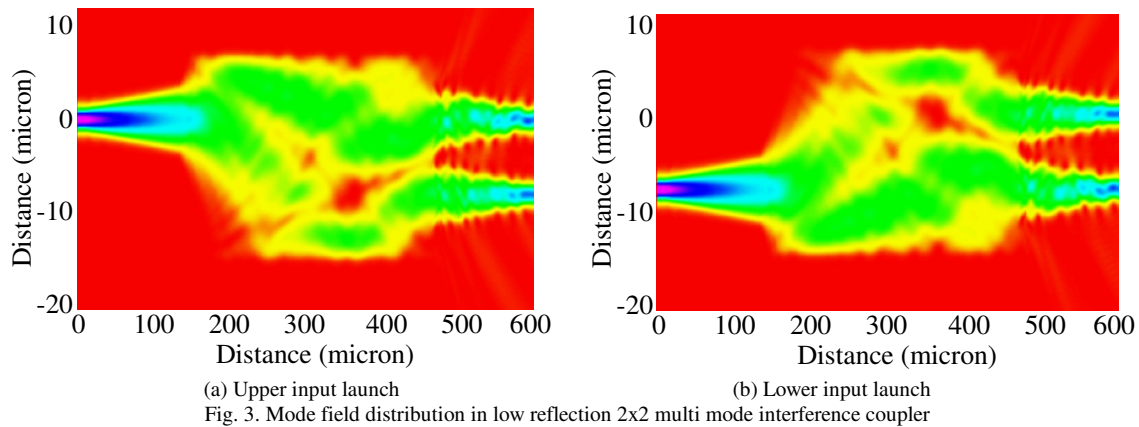
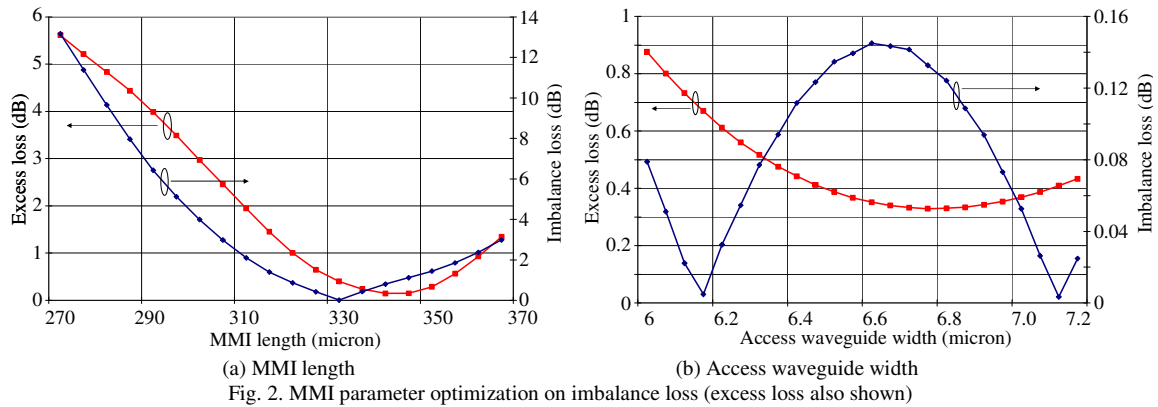


Fig. 1. Experimental setup to measure optical characteristics of multi-stage integrated en/decoders.

## Design of Multi-Mode Interferometer

The 2x2 3dB multi-mode interference couplers are designed with reduced reflection losses [6], and optimized on imbalance via the access waveguide (Wa) width [7]. The lithography demanded a minimal gap of 1μm between the access waveguides. We have first determined the width of the MMI to be 22μm which gave the best results in excess and imbalance losses. The corresponding initial dimensions of a paired MMI are  $L=320.1\mu\text{m}$ ,  $W_a=6.6\mu\text{m}$ ,  $x_{c1} = 7.33\mu\text{m}$ , and  $x_{c2} = 14.67\mu\text{m}$  [7]. We then optimize on imbalance loss via first the length of the MMI and then via the access waveguide width as shown in Fig. 2(a) and (b). An MMI with  $L=330.1\mu\text{m}$ ,  $W=22\mu\text{m}$  and  $W_a=7.1\mu\text{m}$  shows a negligible imbalance and an excess loss of 0.4dB for TE@1550nm. A 125μm long taper is used to connect the waveguide to  $W_a$  which corresponds with values found in [7]. The mode field distribution in the final design is simulated using a beam propagation method in the Phoenix simulation and visualization tools [8]. This is shown in Fig. 3(a) and (b) for a mode launch in the upper and lower input of the MMI.



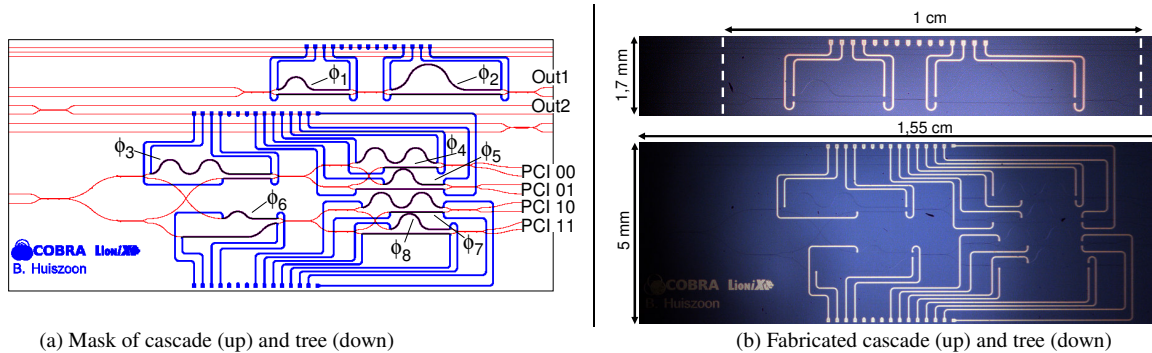
## Two-Stage Cascade and Tree En/Decoders

The mask and the actual two-stage cascade and tree E/Ds are shown in Fig. 4(a) and (b). An output power of  $-2.2\text{dBm} \pm 0.1\text{dB}$  was measured at the 2x2 two-stage cascade E/D, and  $-9.9\text{dBm} \pm 0.4\text{dB}$  was measured at the 2x8 two-stage tree E/D. The loss of the cascade can be estimated as follows: 2x connector losses of 0.8dB, 2x fiber-chip losses of 1.8dB, 2x SSC losses of 1.6dB, 3x MMI excess losses of 1.8dB, a 3dB splitting loss and propagation losses of 1.1dB. The two-stage tree additionally has a 6dB splitting loss, 2x MMI excess losses and higher propagation losses. The four measured and modeled spectral codes of a two-stage cascade and tree are shown in Fig. 5(a)-(d). The spectral codes are labeled via the settings of the phase shifters (or phase code identifiers (PCIs) [2]) as shown in Fig. 4(a). Thus PCI 00, 01, 10 and 11 are represented by the following dissipated powers of the phase shifters, namely  $(\phi_1=31\text{mW}, \phi_2=0\text{mW})$ ,  $(\phi_1=31\text{mW}, \phi_2=124\text{mW})$ ,  $(\phi_1=148\text{mW}, \phi_2=0\text{mW})$  and  $(\phi_1=148\text{mW}, \phi_2=124\text{mW})$  at the two-stage cascade E/D and  $(\phi_3=26\text{mW}, \phi_5=0\text{mW})$ ,  $(\phi_3=26\text{mW}, \phi_5=171\text{mW})$ ,  $(\phi_6=268\text{mW}, \phi_7=47\text{mW})$  and  $(\phi_5=268\text{mW}, \phi_8=41\text{mW})$  at the two-stage tree E/D. We have measured a thermal crosstalk of around  $0.3\text{ pm/mW}$  between  $\phi_4, \phi_5$  and  $\phi_7, \phi_8$  due to a narrow spacing of  $35\mu\text{m}$ . This effect is not noticeable at the low thermal tuning powers used. The spectral codes in Fig. 5 show an excellent match with the modeled codes in [2]. Moreover, the tree and cascade have a comparable performance.

## Conclusions

The passive, periodic and low-loss en/decoders presented in this paper enable a cost-efficient multi-user incoherent spectral amplitude OCDMA deployment on a (coarse-)

wavelength division multiplexing passive optical network. We have integrated multiple multi-stage cascade and tree E/Ds in the Si<sub>3</sub>N<sub>4</sub>-SiO<sub>2</sub> material system. The design, fabrication method and optical characteristics are shown here for the first time. We report an excellent match with the modeled spectral codes for two-stage en/decoders. The tree structure shows a performance comparable to the cascade.



(a) Mask of cascade (up) and tree (down)

(b) Fabricated cascade (up) and tree (down)

Fig. 4. Integrated two-stage en/decoders

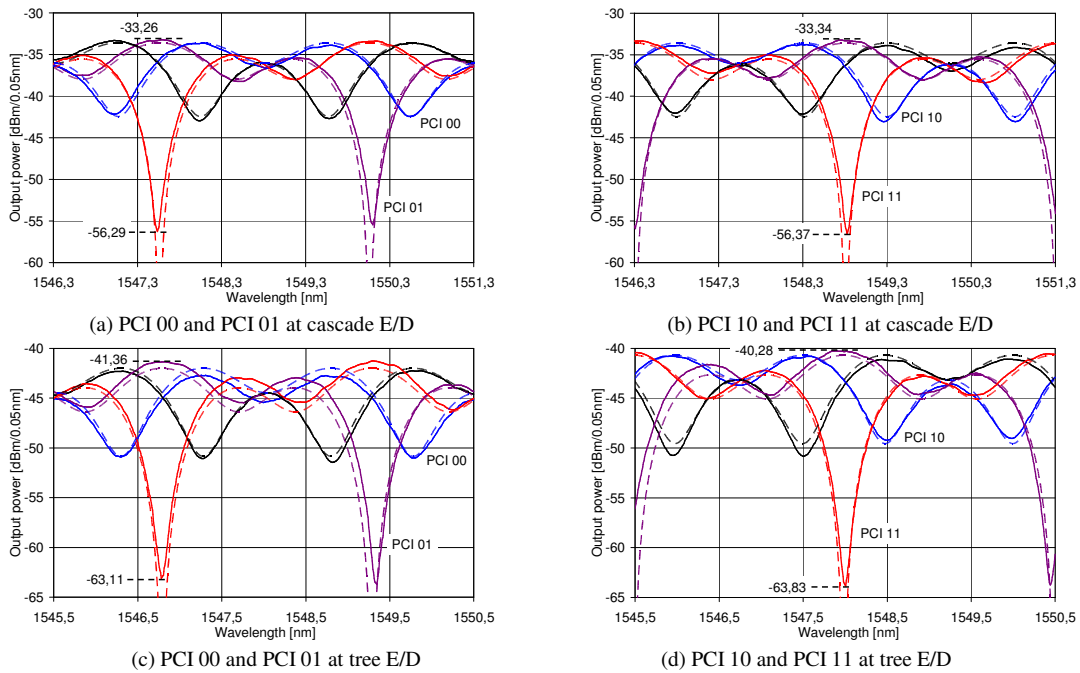


Fig. 5. Spectral codes corresponding with PCIs for two-stage integrated en/decoders; model (dashed) and experiment (solid)

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