1 Gbit/s two-chip MEM-tunable pin-photodiode for WDM

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ABSTRACT
This paper deals with the characteristics and performance of a two-chip bulk-micromachined electrothermally tunable and wavelength selective pin-photodiode. In this realisation, a movable dielectric based Bragg-mirror is fabricated on one chip and a pin-photodiode on the second chip. Combining the two chips assembles the Fabry-Pérot wavelength selective element. The tunability is achieved by varying the length of the resonance cavity between the mirrors with the help of the movable membrane. The device is coupled to a single mode fiber to allows direct employment in wavelength division multiplexing systems. The device features a free-spectral range of 50 nm (fully tunable) and a full-width half-maximum of ±9 GHz. Successful 1 Gbit/s channel monitoring is demonstrated.

Keywords: micro-electromechanical system (MEMS), micromachining, tunable, wavelength selectivity, pin-photodiode, optical receiver, optical front end, optical filter, wavelength-division multiplexing (WDM)

1. Introduction
Wavelength Division Multiplexing (WDM) has become the foremost technology for accessing the huge bandwidth available in the optical fiber. The rapid growth of such high capacity systems has created a huge demand for a variety of new components and devices. One of the key components of WDM systems is a wavelength selective and tunable receiver, which is required for periodic monitoring of the quality of different WDM channels. This paper deals with the characteristics and performance of a two-chip bulk-micromachined electrothermally tunable and wavelength selective pin-photodiode. This device, as well as most of the micromachined wavelength selective methods are based on the well-known principle of Fabry-Pérot (FP) interferometry, which comprises a resonant cavity formed by two mirrors. In this realisation, a movable dielectric based Bragg-mirror is fabricated on one chip and a pin-photodiode on the second chip (see Fig. 1). The pin-photodiode chip contains additionally a dielectric Bragg-mirror on the bottom side. Combining the two chips assembles the Fabry-Pérot wavelength selective element. The tunability in this case is achieved by varying the length of the resonance cavity between the mirrors with the help of the movable membrane 1. The optical-electrical conversion takes place outside the cavity in the intrinsic layer of the photodiode chip, differentiating this concept from other conventional wavelength selective detectors, e.g. resonant-cavity (RC) pin-photodiode 2. For the experiments the device was coupled to a single mode fiber, to allows direct employment in a WDM data transmission environment.

2. DEVICE STRUCTURE
The bulk-micromachined membrane chip consists of a dielectric Bragg-mirror (8.5 periods of Si$_3$N$_4$/SiO$_2$, deposited on InP substrate with a Plasma Enhanced Chemical Vapour Deposition System). The calculated reflectivity of the Bragg-mirror is around 99 %. The manufacturing was done by using a wet-etching process. On top of the membrane suspensions a thin metallic layer (Cr/Au) was deposited. In this metallic layer the dissipated electrical power creates the necessary heating of the dielectric membrane structure to increase the resonator length, leading to the tuning of the resonance wavelength. Details of the membrane process and performance can be found in 1. The InP grown InGaAs/InAlAs pin-photodiode features a 1.7 µm thick intrinsic absorption layer. On the bottom of the pin-photodiode substrate a 7 pair Ta$_2$O$_5$/SiO$_2$ Bragg mirror was sputtered (reflection around 99 %). The manufacturing of the pin-photodiode was carried out at CEERI, Pilani, by utilising a wet-etching process. On top of the pin-photodiode substrate a $\lambda$/4 thick Si$_3$N$_4$ layer was deposited, serving as an anti-reflection coating to avoid any parasitic resonance cavity effects due to internal reflection on the semiconductor-air surface. The 180 µm pin-photodiode device was biased with −5 V,
resulting in a 3-dB bandwidth of 1.2 GHz, suitable for 1 Gbit/s transmission. The electrical connections were made with coplanar contact needles (see Fig. 2, top). The p-contact on top of the 180 \( \mu \text{m} \) diameter pin-mesa is designed as a ring-structure to have a transmission window to support the optical alignment. The two-chip device was assembled with the help of a near-infrared (NIR) translucent microscope (see Fig. 2, top). This allows the passive alignment of the two chips. The NIR light is blocked in the metallised suspension beams, as well as in the metallised outer ring of the membrane. The dielectric membrane itself is translucent to the NIR light. The InP substrate of the pin-photodiode is almost translucent. However the intrinsic InGaAs layer is highly absorptive at these wavelength, and works as a good alignment contrast, as well as the pin-photodiode coplanar contact pads. Permanent connection after passive alignment is established by using a ultraviolet (UV)-curable glue. The device is then located in a tailored Gaussian beam, which exactly matches the geometrical dimensions of the cavity. To obtain the necessary membrane curvature data, measurements with a profilometer to determine the bending radius have been conducted. Based on these values the necessary Gaussian beam, mandatory for high lateral side mode suppression, was calculated and created by employing the appropriate lens system.

3. STATIC PERFORMANCE
To evaluate the static responsivity of the wavelength selective and tunable pin-photodiode the photocurrent was recorded while scanning the wavelength regime with a tunable laser. The step size for the sampling of the wavelength region was 0.05 nm. The measured response for several tuning currents are presented in Fig. 3. The peak responsivity was around -18 dB (0.13 A/W). Assuming a theoretical maximum responsivity of 0.62 A/W (1.7 \( \mu \text{m} \) intrinsic-layer thickness, assuming 85 % efficiency), results in an insertion loss of 6.5 dB (optical domain). The losses are quite high and can be explained by the rough hand-polished surface properties of the pin-photodiode substrate before sputtering of the Bragg-mirror. Another reason can be found in the misalignment of the optical axis between pin-photodiode chip and membrane chip, which causes that only a fraction of the light beam is detected in the pin-mesa structure. The measured full-width half-maximum (FWHM) of the transmission is around 0.15 nm (\( \pm \) 9 GHz), suitable for up to 2.5 Gbit/s transmission. The measured free-spectral-range (FSR) is around 50 nm, resulting in a device finesse of around 300. The dissipated actuation power vs. tuning relationship is linear with \( S = 2.3 \text{ mW/nm} \). The non-equal insertion loss of the device during tuning is attributed to the discrete sampling steps of the tunable laser (0.05 nm). The device features a cross talk below -40 dB from 100 GHz spaced adjacent channels (see Fig. 4). The present higher order lateral side modes are caused by the incoupling lens system. The employed lens system produces a Gaussian beam, containing also higher order modes beside the fundamental mode. These higher order modes excite also higher order modes in the
cavity. Measurements of the far-field of the lens system have proven this assumption. The first reasonable side mode is a side mode of second order, indicating a perfect alignment, as the first side modes are suppressed. In an optical filter, where light passes the discrete filter device and is coupled back into a single mode fiber again, these higher order modes are suppressed sufficiently, due to their low coupling efficiency into a single mode fiber. Hence direct detection inside the intrinsic layer detects all the present higher order modes.

![Graph](image1.png)

**Fig. 3:** Responsivity of the device vs. tuning current, \(20 \log (R / 1 \text{A/W})\).

![Graph](image2.png)

**Fig. 4:** Wavelength selectivity and crosstalk from channels spaced 100 GHz apart, high resolution, 0.02 nm sampling step size.

### 4. Employment in a WDM System Environment

The device has been employed in a WDM system like environment (see Fig. 5). Three WDM wavelengths (1550.12 nm, 1550.92 nm and 1551.72 nm) have been combined and modulated by a Mach-Zehnder modulator (MZM). The modulation format was non-return to zero (NRZ) with 1 Gbit/s data rate for each channel (pseudo-random bit sequence, 223-1 PRBS). After amplification with an erbium-doped fibre-amplifier (EDFA) to 0 dBm/channel (to avoid any deteriorating nonlinear effects along the fiber) the signals were sent over 50 km standard single mode fiber (SMF-28). After a second EDFA and the following attenuator the signals were launched into the fiber-coupled tunable and wavelength selective receiver. The pin-photodiode was directly connected to a 50 \(\Omega\) oscilloscope to monitor the photocurrent. The dispersion of the 50 km SMF-28 (17 ps/nm/km) leads to a shift (decorrelation) between the channels of around 680 ps, which is around half of the 1 ns bit duration. This is intended to create maximum distortion from neighboring channels. Additionally, the influence of polarization dependent effects on the device can be seen by employing a long fiber span. The device was operated without any automatic frequency control (AFC) circuit, which is usually necessary for such a device. Thus no long-term experiments were carried out (e.g. bit-error measurements (BER)), as the selected wavelength (filter resonance) is strongly dependent on room temperature. Instead the eye-diagram was monitored, in a back-to-back configuration (SMF length = 0 km), and after 50 km, with a PRBS and a 1010 bit sequence. Both experiments unveil that the influence from any neighboring channel is sufficiently suppressed. Fig. 6, 8, 9 and 11 present the eye-diagrams (PRBS) and curve traces (0101-bit sequence) detected by the device. Fig. 7 and 10 display the signal at the input of the device (“optical eye” of the three decorrelated channels). There is no degradation (influence from neighboring channels) visible, all selected channel data signals were clearly visible. Even in a single channel environment a wavelength selective receiver can improve the system performance as the EDFA noise level is filtered and thus reduced.

![Diagram](image3.png)

**Fig. 5:** Experimental WDM configuration.
5. CONCLUSION AND OUTLOOK

A tunable and wavelength selective receiver for data rates of 1 Gbit/s has been presented. The wavelength selectivity has been demonstrated to be sufficient for monitoring the quality of WDM channels. A FSR of almost 50 nm, together with the finesse of 300, has been obtained. The crosstalk suppression of more than 40 dB has been proven to be sufficient for this type of application.

A further goal is to implement more functions into the receiver chip, like amplification and signal shaping. This is currently the focus of ongoing research projects between TU Darmstadt and CEERI, Pilani. Further applications of this micromechanics two-chip concept include the successful demonstration of tunable optical filters and tunable vertical-cavity surface-emitting lasers (VCSELs), electrically and optically pumped.

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