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A dual purpose, all optical multiplexer circuit in InP, for multiplexing clock and NRZ data, and for transmultiplexing WDM to TDM

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Abstract: We present a new, integrated all-optical multiplexer for wavelength grooming of many WDM channels into a single TDM channel. The chips were realized in a novel generic InP foundry process. For design and mask layout of the multiplexer circuits, we developed a simple equivalent circuit, representing the incorporated wavelength converter. With the chips realized, successful WDM to TDM transmultiplexing is demonstrated, as well as multiplexing of clock and NRZ data.

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OCIS codes: (250.3140) Integrated optoelectronic circuits; (250.5980) Semiconductor optical amplifiers; (250.0250) Optoelectronics.

References and links

1. Introduction
With the ever increasing bit rate per wavelength division multiplexed (WDM) channel, all optical signal processing becomes attractive. A specific function in which all-optical signal processing is very attractive is so called “wavelength (λ) grooming”. A set of tributary lower bit rate WDM, non-return-to-zero (NRZ) channels is “λ groomed” into a single, time domain...
multiplexed (TDM) channel at the aggregate bit rate. Typically this function is to be performed in the upstream traffic of (future) Central Offices. In there, the various WDM NRZ contributions from the connected local area networks (LAN’s) are transmultiplexed into a single λ outgoing metropolitan area network (MAN) TDM channel at the aggregate bit rate. In its turn the MAN TDM channel is one of the constituent channels of a MAN WDM comb. In the literature, a network concept that exploits this transparent grooming of traffic between access network and a metro core ring network is described in ref [1]. Whereas a regenerative optical grooming switch for buffer-less interconnection of metro/access and metro/core ring networks is demonstrated in [2].

For the WDM-to-TDM conversion, as an underlying principle for λ grooming, various techniques have been experimentally demonstrated: e.g. by using fiber nonlinearities [3] or by using electro absorption wavelength conversion [4]. Optic-electronic-optic (OEO) conversion, used for wavelength conversion and simultaneously for asynchronous retiming, is demonstrated in [5]. Other concepts for retiming and reshaping of WDM signals for WDM-to-TDM conversion are found in [6–8]. Single channel optical wavelength conversion (WLC) concepts, based on cross phase modulation (XPM) and cross gain modulation (XGM) in semiconductor optical amplifiers (SOA) can be found in [9], and references in that paper. Conversion of the modulation format with wavelength conversion in SOA’s is demonstrated in [10].

In this paper we present the design, realization and testing of the first integrated indium phosphide (InP) based multiplexer circuits, which can perform such a WDM → TDM transmultiplexing function in an all optical way. As depicted in Fig. 1, the integrated optical circuits can serve a dual purpose in this respect. With the same ‘all optical’ InP circuit, we demonstrate the actual transmultiplexing step of ‘multiple λ WDM → single λ TDM’, as well as its preceding step of multiplexing ’clock x NRZ data → narrow pulse return-to-zero (RZ) data’.

Fig. 1. A dual purpose integrated InP multiplexer chip, and its potential use for wavelength λ-grooming the upstream traffic in the interfaces from access to metro network.

2. Design of ‘all optical’ multiplexer circuits and manufacturing in generic InP technology

For the realization of the all-optical multiplexer circuits in a single chip, we have embarked on ‘generic’ InP photonic integration technology [11]. The ‘generic technology’ basically relies on separating circuit design from consolidated fabrication technology. It ideally consists of some six consecutive and well-defined steps: circuit conception, validation and verification...
of circuit and of layout with device and circuit simulation tools, circuit layout and mask generation, running a consolidated process in an InP foundry, testing of the fabricated devices, and packaging.

InP is the material system of choice for the chip, because of its unique ability to combine “active” (gain and/or phase, electrically driven) and “passive” optical functionality. And the choice for fabrication in a generic foundry technology is simply a matter of fabrication yield: complex optical circuitry can only be made with good yield if the fabrication of its constituent components is extremely reliable (and is guaranteed by the manufacturer to the designer).

The designs for the multiplexer circuits were tested and verified with commercially available VPI software tools. But as described below, we also developed simple compact models for gain and gain suppression, wavelength conversion and subsequent optical filtering of converted signals. Here the advantage of such a compact model is twofold: simplicity, but moreover specifically the inclusion of carrier heating effects (next to carrier number effects), while not available in VPI software.

The actual realization of the circuit is done in a number of iterative steps, with a number of subsequent process runs in ‘generic InP technology’. We have chosen for this iterative approach, since ‘generic InP technology’ is still in an infantile stage, with e.g. an increasing number of standard building blocks per run. A full description of these modules/building blocks in terms of compact model was not (yet) available at the time of the chip design. In fact some of the properties of the gain- or the phase shift- sections which are of specific interest to the present chip designs, could only be determined, (= measured), after realization of the chips.

As shown in Fig. 2 in generic InP foundry technology there is a clear separation of duties:

1) concept, design, mask layout, and mounting, test, assessment (TU/e in Eindhoven/NL),
2) wafer, bar, die and chip fabrication in well established, standard building blocks and process modules (OCLARO in Caswell/UK).

- The “passives” building blocks used were deeply etched waveguides (WG) for connections, ‘shallow-deep’ transitions, 1x2 and 2x2 multi mode interference (MMI) couplers, and angled and straight optical input/outputs (I/O’s).
- For the “actives” we used matched pairs of shallow ridge gain (GAIN) sections, and matched pairs of deeply etched ridges for the forwardly biased phase shifters (EOM).

<table>
<thead>
<tr>
<th>Building Blocks</th>
<th>OCLARO •fabrication</th>
<th>TU/e •concept •design •layout</th>
<th>TU/e •mount •test •assess •package</th>
</tr>
</thead>
<tbody>
<tr>
<td>WG MMI GAIN</td>
<td>RUN #0/1 TMC: 6 chips</td>
<td>#6 (#3)†</td>
<td>#2</td>
</tr>
<tr>
<td>RUN #1/2</td>
<td>TMC: 5 chips</td>
<td>#10a</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Overview of trans multiplexer circuits in two consecutive Memphis project runs.
An overview of mask layouts and pictures of dies with the multiplexer circuits is also shown in Fig. 2. The chips were made in two consecutive Memphis Project Runs, together with very different circuits (not shown) from other Memphis optical circuit designers. From run to run the number of available building blocks from OCLARO steadily increased. Typically 5 or 6 trans modulator circuits (with a total area of 4x4 mm$^2$) were realized in each run, together with very different circuits from other designers on a 12 x 12 mm$^2$ reticle (also not shown).

Each multiplexer circuit consists of a wavelength converter with electrically tunable optical filters at its output. In its turn the wavelength converter consists of a matched pair of two identical GAIN wave guides, with 50/50 split ratio MMI’s at in- and output. In this way each WLC also acts as spatial (directional) filter, in order separate at the WLC output, the new and the old signal wavelength in a wavelength agile fashion. The tunable output optical filters in the various circuit designs contain a variation of parallel and of series differential filtering, 1st or 2nd order, anti symmetric and symmetric, and with various time delays/gates. Folded and stretched configurations, for wavelength converters and for optical filters, were realized.

### 3. Mounting, testing and chip characterization

For the characterization we developed dedicated carriers, test fixture, electrical drive/measurement equipment (hard & software) and an opto-mechanical test station. In the opto-mechanical test station lensed multi (~4) fiber arrays are coupled to the North, and to the South side of the chip. See Fig. 3. Electrical connections to the chips are made at the East and West side. On the carriers the (~16) bond contacts from the chip are fed into standard flexible print connectors. Since all signal processing is optically only, there are no high speed electrical contacts to the chips. All electrical contacts are dc and provide the necessary control of gain sections and of the phase shift section pairs at the various stages in the chip.

![Building blocks: WG, MMI, SOA](image1)

**Optical I/O’s: Lensed 4-Fibre Arrays**

4x4 mm DIE ➔ Chip on Universal Carrier

![Fig. 3. Example of angled, lensed fiber arrays coupled to chip on universal carrier.](image2)
4. The circuit on the chip

Fig. 4. Schematic design of an ‘all optical’ multiplexer circuit. From left to right: input amplifiers at E and B, WLC annex spatial filter, first delay interferometer filter with delay τ, second delay interferometer filter with delay 2τ, output amplifiers at C.

Fig. 5. Optical microscope top view of a 1x4 mm² InP ‘all optical’ transmultiplexer chip (label #10 C). Each gain section has a single (larger) rectangular bond pad, whereas each phase shift section has two (small) circular bond pads (of which actually only one is used in mounted devices).

A schematic design of a transmultiplexer circuit is shown in Fig. 4, whereas the corresponding microscope picture of a realized chip, labeled #10C, is displayed in Fig. 5.

The transmultiplexer circuit combines three well defined functions, wavelength conversion, spatial filtering, carrier suppression and equalization in the frequency domain:

• Transcription of the optical base (B) input data to a new carrier wavelength at the collector (C) output. This WLC conversion is based on XGM and XPM in the matched (identical) SOA pair, i.e. the pair with the largest rectangular contact pads in Fig. 5.

• Separation of the input wavelength (B → drain D) and the output wavelength (emitter E → collector C), by using a parallel matched pair of gain sections in a phase tunable equal arm length MZ configuration as spatial (directional) filter. In series with the gain section, a phase shifter matched pair is included in this Mach Zehnder (MZ) to compensate for phase variations in the two arms, related to fabrication tolerances and/or temperature gradients in the chip under operation. An electrically induced phase shift of π can also be used to switch the MZ from cross to bar state and hence interchange e.g. inputs E and B. A big advantage of the included spatial (directional) filter is that it removes the need for an external wavelength selective filter at the device output, in order to remove the input data signal wave length. And hence it in principle also allows replacement of an external erbium doped fiber amplifier (EDFA) at the device output, by an integrated on chip (internal) in-line and/or booster SOA.

• Optical equalization of the slow gain recovery and suppression of the carrier, with (cascaded) tunable unequal arm length MZ filters acting as differential
interferometer (DI) filter and to some extent as FM→AM converter. Periodicity, and 360 degree tuning of the phase shift differences, gives proper (and electrically tunable) filter operation, with full C-band (~1550 nm) coverage.

- The cascaded DI filters have delays of $\tau$ and $2\tau$ respectively. Hence their output is a combination of four WLC output fields: $E(t)$, $E(t-\tau)$, $E(t-2\tau)$ and $E(t-3\tau)$. As discussed and demonstrated below, their relative phases and amplitudes as determined by the settings of the phase shifters in the filters, determine the resulting filter output field, as function of time.

- In both differential filters with delays $\tau$ and $2\tau$ respectively, the actual DI filter is preceded with an equal arm MZ. The function of the latter MZ is to control the power ratio in the two arms of the following unequal arm DI-MZ. Either in order to apply deliberate differences, or for compensating for unequal losses in the two arms of the differential interferometer and/or for compensating imperfect 50/50 split ratios of the MMI’s. In chip testing, the power ratio control function can also be used for switching off for instance the first DI (with delay $\tau$), in order to test the operation of the second DI (with delay $2\tau$).

5. Compact model for wavelength conversion, as input for DI filter designs

As input for design and for evaluation of the included differential optical filters, we modeled the wave length converters with simple WLC equivalent circuits. For the inputs of these circuits we start with well behaved optical pulses. The resulting ill behaved WLC outputs (dips and slow recovering steps) of these equivalent circuits are then subsequently used as input for the above described cascaded DI filters. The purpose is of course to regain nice output pulses, with both perfect and less perfect working filters.

The starting point for WLC compact model is a simple Taylor expansion of the device XGM and XPM response in a given operating point. In the frequency domain, the carrier number contribution to this response (i.e. the field modulation index $m$, as function of input power variation) can be cast in the form:

$$
Re \, m(\text{out}) = \frac{\Delta E}{E_0} = \left(-\frac{1}{2}\right) \Gamma' \left(\frac{dG}{dN}\right)(G-1) \frac{\Delta P_{\text{in,base}}}{j\omega + \tau^-} \quad (1)
$$

$$
Im \, m(\text{out}) = \phi = \left(-\frac{1}{2}\right) \Gamma'' \left(\frac{dG}{dN}\right)(G-1) \frac{\Delta P_{\text{in,base}}}{j\omega + \tau^-} \quad (2)
$$

where $\tau$ is the carrier number recovery time

Similar expressions, one for the real and one for the imaginary part can be written down for the carrier temperature contribution to the XGM and XPM response. The recovery time then of course is the much faster electron temperature recovery time. Adding the two physical effects, and transforming to the time domain then yields a simple WLC equivalent circuit in the form of a transimpedance (from $\Delta P$ at B, to $m$ at C). Actually there are two transimpedance circuits: one for the real, and one for the imaginary part of the output modulation index $m$. We maintain the notation: input base (B) and output collector (C). The transimpedance equivalent circuits are represented in Fig. 6. Basically the representation is simply two different parallel RC filters in series. Having in mind input pulses (B) in the range (2-20 ps) both carrier number ($R_1C_1$) and carrier temperature ($R_2C_2$) effects are included. The output of the WLC compact model is used as input for the subsequent cascaded DI filtering.
**Wave Length Converter**

*equivalent circuit for 'transimpedance' [ \( m(\text{out}, C) / \Delta P(\text{in}, B) \)]*

\[
\begin{align*}
C_1 &= (dG/dN)^{-1} \\
R_1 &= \tau_{\text{REC}}(dG/dN) \\
C_2 &= \left(\nu_T(dG/dT_c)/(dT_c/dP)\right)^{-1} \\
R_2 &= \tau_{\text{TEMP}} C_2^{-1} \\
\end{align*}
\]

*carrier number: recombination/injection (slow)*

*carrier temperature: heating/cooling (fast)*

**Input:** optical pulse power \( \Delta P(\text{in}) \)

**Output:** field modulation index \( m(\text{out}, C) \)

\[
\begin{align*}
\text{for } \tau_{\text{TEMP}} \ll \text{ time } \ll \tau_{\text{REC}} & \\
\text{instantaneous } \Delta t_{\text{PULSE}} < \tau_{\text{SERIES}} & \\
\text{integrating } \Delta t_{\text{PULSE}} > \tau_{\text{SERIES}} & \end{align*}
\]

**Output:**

field modulation index \( m(\text{out}) \)

\[
\begin{align*}
\text{Re } m(\text{out}) & \rightarrow \Delta E/E \\
\text{Im } m(\text{out}) & \rightarrow \Delta \phi \\
\end{align*}
\]

Fig. 6. Wave Length Converter Equivalent circuits: one for the real and for the imaginary part of the field modulation index. For the real part all \( G = G' \) whereas for the imaginary part all \( G = G'' \).

For times \( t \) for \( \tau_{\text{TEMP}} \ll t \ll \tau_{\text{REC}} \) the equivalent circuits basically can be represented as a series RC circuit with an instantaneous (over \( R_2 \)) and an integrating component (over \( C_1 \)) in the resulting output modulation index. And the ratio of pulse width \( \Delta t_{\text{PULSE}} \) and \( \tau_{\text{SERIES}} = R_2 C_1 \) determines the shape of the response \( m(\text{out}, C) \), i.e. the relative strength of the instantaneous and the integrating contribution. This effect of the input pulse width, on the time dependence of the phase of the converted output is demonstrated in Fig. 7.

Fig. 7. The evolution from X-phase modulation to X-frequency modulation, with increasing input pulse width (B). Examples of simulation results for wavelength conversion, with X-phase and X-frequency modulation of comparable strength, and followed by differential filtering are shown in Fig. 8. Typically anti-symmetrical filtering (first, as well as second order) yields a kind of “echo” in the trailing edge of the pulse. Whereas this “echo” is virtually absent with symmetric second order filtering. Moreover the latter filtering shows a much better background extinction ratio, even when relatively imperfect constituent MZ filters with only very moderate maximum extinction ratio (down to only e.g. \(-14\text{ dB}\)) are used.

A simple experimental demonstration of changing from anti-symmetrical to symmetrical 2nd order differential filtering will be described below, in section 8. ‘Equalization and carrier suppression with electrically tunable filters’. 

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6. Experimental set up: subcomponent, integrated component and overall testing

A photographer’s impression of the experimental set up, in its built up phase is shown in Fig. 9, with from left to right a general overview, next the tables of the two six-axis stages for fiber array alignment together with a carrier test fixture. And the third picture shows the chip carrier with flexible printed circuit (FPC) contact. The picture most to the right shows the two lensed fiber arrays coupled to a trans multiplexer chip.

A schematic overview of the test up we used is shown in Fig. 10 and Fig. 11. In all test the chips are electrically connected to a 16 channel dc source monitor unit. We performed extensive chip measurements of the various sub-components integrated on the chip (like gain as function of current, electrical tuning of the MZ filters) as well as the more integrated components with functionalities like the spatial filtering, and the equalization/carrier suppression. Finally we tested the dual multiplex capability of the chips: trans multiplexing WDM to TDM and multiplexing clock and NRZ data. Test results for these integrated functionalities are described in the corresponding sections below.
The experimental set for testing multiplexing clock and NRZ data to narrow pulse RZ data is shown in Fig. 11. The main difference with the trans multiplexer set up of Fig. 10 is in the input signals to the MUX chip.

7. Separation of in- and output wavelengths by spatial filtering

The operating principle of the incorporated spatial filter was already described above in the description of the circuit on the chip (section 4.). Here we give an experimental demonstration. Since the separation relies on phase rather than wavelength, there is the full separation of the signal input \((B \rightarrow D)\) old, and the signal output \((E \rightarrow C's)\) new lambda’s over the whole gain (C-band) bandwidth. The spatial filtering is achieved by using a parallel matched pair of gain sections in a phase tunable equal arm length MZ configuration, with 2x2
MMI’s as I/O’s. An experimental demonstration with approximately 30 dB Extinction Ratio in the B/D and E/C separation is shown in Fig. 12.

Optical test results regarding spatial (directional) filtering were displayed in Fig. 12. As a further clarification of this Fig. 12, we include a schematic overview of the trans multiplexer circuit in Fig. 13 while using the symbols of Fig. 4 for the various building blocks in the circuit. Moreover, for further section identification by the reader, the bond wire schedule as used on the ‘universal carrier’ is shown.

Fig. 13. Schematic overview of the electrical connections to wavelength converter plus spatial filter, to the first differential interferometer filter and to the second differential filter.
8. Equalization and carrier suppression with electrically tunable filters

Without the incorporated optical filters #1 and/or #2 (see Fig. 4 or Fig. 13), the transcribed / multiplexed output signals (from the C’s) would be heavily distorted due to the slow gain recovery time of the gain sections (typically ~400 ps for a 10-90% time). Optical equalization of the slow gain recovery, and suppression of the carrier, is done with one or two tunable unequal arm length MZ filters acting as differential filter. By adjusting the biases to the phase shifters, we can choose between anti-symmetric (1st and 2nd order) and symmetric (2nd order only), at any arbitrary chosen output λ. Periodicity, and 360 degree tuning of phase shifter pairs, gives proper (and electrically tunable) filter operation, with full C-band (from 1535 to 1565 nm) coverage.

In particular for the intermediate range of 2-20 ps input pulse widths, symmetric second order filters show superior performance, in terms of carrier suppression and of reduced intersymbol interference. An example is shown in Fig. 14, where by changing the Δ current of (East3-West15) from 0.0 to −11.0 mA, the filter switches from anti-symmetric to symmetric second order.

![Fig. 14. Electrical tuning of Second Order from Anti-symmetric to Symmetrical Filter operation, with associated filter characteristics, output spectra and eye diagrams with RZ 20 Gb/s PRBS data](image)

9. The dual multiplex capability of the chip

The transmultiplexing of two WDM channels into a single TDM channel is shown in Fig. 15. Whereas the multiplexing of clock x NRZ data to short pulse RZ data is demonstrated in Fig. 16. As is clear from the Fig. 15 (and from Fig. 16), in the WDM to TDM transmultiplexer there is ample space for many more than the two WDM input channels, as we used in our demonstration.
10. Conclusions

The first integrated, ‘all optical’ WDM to TDM transmultiplexer circuits, realized in generic InP technology were presented. For design and mask layout of the multiplexer circuits, we developed a simple equivalent circuit, representing the incorporated wave length converter. We experimentally demonstrated the dual purpose ‘all optical’ multiplexing capabilities of the same chip: grooming of WDM → TDM, as well as the multiplexing of Clock x NRZ data → narrow pulse RZ data.
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