Recent developments in InP-based devices for fibre optic communication


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Cost - in contrast to functionality - has become one key issue for fibre optic communication devices and systems. One example of devices meeting this demand are lasers designed for uncooled operation and direct modulation at 10 Gbit/s, which could either be single InP chip solutions or hybrid fibre-grating lasers. Also of interest are lasers with integrated spot size transformers suited for passive alignment under relaxed tolerances, and another category of important devices are widely tunable lasers with simple tuning schemes which can lower inventory cost or enable simple wavelength selection.

High-speed devices for single channel bit rates of 40 Gbit/s and beyond have moved somewhat out of focus, but are nevertheless still attracting interest, and these components include photodetectors, where 100 GHz band width has recently been demonstrated, modulators, and pulse sources for Optical Time Domain Multiplexing (OTDM). An example enabling 160 Gbit/s single channel bit rate are mode-locked lasers with about 1…2 ps pulse width and appropriate repetition frequency adjustability.

Self-pulsating lasers for all-optical clock extraction are particularly attractive as they replace expensive electronic devices in ultra-high bit rate communication systems. The present talk will cover the devices mentioned and illustrate relevant or competing concepts and recent achievements as well.

key words: InP-based optoelectronic devices, semiconductor lasers, photodetectors

1. Introduction

Indium phosphide based optoelectronic integrated circuits (OEICs) are key components for fibre optic communication systems operating in the 1.3 and/or 1.55 μm wavelength range. Systems deployed in recent years operate at single channel bit rates up to 10 Gbit/s. (Dense) wavelength division multiplexing ((D)WDM) has found widespread use, and it is primarily restricted to the so-called C- and L-bands (1530-1565 nm and 1565-1625 nm, respectively) due to the availability of EDFA amplifiers covering these wavelength ranges. Developments for further upgrades of fibre optic networks have focused in the past on raising the single channel bit rates (to 40 and 160 Gbit/s) and on preparing for all-optical functionalities. These goals have become less appealing recently and currently devices are considered most attractive if they enable cheaper system cost (installation, operation, maintenance). In addition, METRO and access networks have moved more into focus while the upgrade of core networks seems to be less urgent in general.
As a consequence lasers suited for uncooled operation, for Coarse WDM (CWDM) with channels distributed over the whole wavelength range from about 1260 to 1625 nm and laser chips suited for passive fibre chip alignment are of high current interest. Widely tunable lasers are another appealing component, primarily as a means to reduce inventory cost. High bit rate transmission is also still of interest, but not only for long distance transmission, but for various shorter distances, e.g. within Ethernet standards (10 Gbit Ethernet, 100 Gigabit Ethernet, …). Finally, research is still continuing towards all-optical techniques, although industrial interest in such components seems to be somewhat low at present. Self-pulsating lasers (SPL) for all-optical clock extraction and for all-optical signal regeneration as well are one example of the latter category. There is also a lot of work on devices based on Photonic Crystal structures, however, it is difficult to predict at what time corresponding commercial devices might be available.

The present paper will highlight some recent device developments in the areas of i) uncooled lasers suited for direct modulation, ii) lasers with integrated spot size converter, iii) widely tunable lasers, iv) high speed modulators, v) components for Optical Time Division Multiplexing (OTDM) enabling 160 Gbit/s single channel bit rate, vi) high speed detectors, and vii) self-pulsating lasers representing a key component for all-optical clock regeneration.

2. Uncooled lasers for direct modulation

Lasers to be directly modulated at 2.5 and at 10 Gbit/s, needing no thermoelectric cooler and to be operated between $-40\ldots-5 < T < +60\ldots+85 \degree C$ (depending on standard chosen) constitute a relevant actual research topic. Lasers are developed in the GaInAsP/InP and in the AlGaInAs/InP material systems and for operation around 1.3 and 1.55 µm. The main challenges are on the one hand to assure sufficiently good operation characteristics at high temperature (threshold current, slope efficiency, modulation speed, appropriate damping) and at the same time to assure good modulation characteristics over the whole operation temperature range, which is more demanding than achieving appropriate modulation behaviour at high temperature only.

![Fig. 1. P-I characteristics of an AlGaInAs/InP RW FP laser](image-url)
Fig. 1 illustrates the P-I characteristics of an AlGaInAs/InP laser in the 20 °C ≤ T ≤ +90 °C temperature range (T₀ > 75 K) and demonstrates that sufficiently high output power is achieved even at +90 °C.

A well-established practical way to assess the principal large signal high-bit rate modulation capability of laser heterostructures (as far as the intrinsic relaxation frequency is concerned) without the need to process low-capacitance laser structures and without proper large-signal modulation is the measurement of RIN spectra (under DC laser operation). Corresponding spectra measured for different driving currents on a GaInAsP/InP laser structure are shown in Fig. 2. The main challenge is to meet all demands at the same time in a single device in contrast to achieving world records for one parameter without care for the rest.

The maximum achievable direct modulation frequency seems to be limited to about 10 Gbit/s for this type of (single section) laser. However, direct modulation at significantly higher bit rates (of the order of 40 Gbit/s) is possible in multi-section laser structures if the dynamics are governed by photon-photon resonance instead of the normally used electron-photon resonance [1].

3. Lasers with integrated spot size transformer

Standard lasers are fabricated with constant cross section all along the chip. If a mode transformer ('taper') is integrated monolithically to the laser, the coupling efficiency is raised and the alignment tolerances for fibre-chip coupling or for hybridly mounting lasers on optical boards (in SiO₂/Si or Silicon-On-Insulator, SOI, for example) are relieved from the submicron regime to about 1…2 µm. Efficient coupling is particularly needed in Fibre-Grating-Lasers (FGL), where the fibre-chip coupling is within the laser cavity. FGL are an alternative variety of lasers for uncooled operation. The temperature-dependent shift of the emission wavelength is determined by the characteristics of the Bragg grating in the optical fibre. It is of the order of 0.02 nm/K, i.e. about one order of magnitude lower than that of standard InP-based lasers.

Tapers have been designed and fabricated in various different ways, the most straightforward design, which is suited for Fabry-Perot lasers, is to have a linear variation
of the active layer width all along the cavity. If the width (of a 1.55 µm GaInAsP/InP BH laser) varies from about 1.5…2.5 µm at the rear facet to about 0.6 µm at the front facet the far field angle is about 15…18 degrees with very low horizontal/vertical/ asymmetry [2] while 30/36 degrees are observed for a similar laser structure with constant active stripe width. In the case of DFB lasers the variation of the effective refractive index along a tapered structure has to be taken into account by properly designing the DFB grating [3], i.e. with a tailored chirp.

4. Widely tunable lasers

Tunable lasers are enabling components for wavelength agile optical networks and in addition they reduce overall inventory cost. Wavelength tuning over a few nm range is easily accomplished for standard DFB (or DBR) lasers, however, lasers which cover the whole C- or L-band, i.e. have a tuning range exceeding 30 nm, are much more attractive and such lasers are developed in various laboratories [4-6]. One example, a Sampled Grating DBR (SG-DBR) laser is shown in Fig. 3 [4]. Such lasers have also been monolithically integrated with a Semiconductor Optical Amplifier (SOA) and with an SOA they provide 10 or even 20 mW CW fibre-coupled output power. The tuning range exceeds 35 nm and the lasers are available either for the C- or the L-band.

![Fig. 3: Widely tunable Sampled Grating DBR laser (manufacturer: agility)](image)

Another concept for a widely tunable laser is shown in Fig. 4 [6]:

![Fig. 4. Widely tunable modulated grating Y-branch laser [6]](image)

The modulated grating Y-branch laser offers particularly good side mode suppression ratio. The reason for that is that the principle relies on the additive Vernier effect, in contrast to the SG-DBR laser for example, which relies on the multiplicative Vernier effect [6].
There are a number of other variants, and all developments have the following main targets: The respective laser should have a rather simple tuning scheme so that the look-up table needed can be generated in a cost effective way. In addition the lasers should exhibit low variations of operating parameters as a function of time, since the end-of-life of these lasers is normally obtained when the emission wavelength experiences a mode jump.

5. High bit rate Mach-Zehnder modulator

40 Gbit/s modulators are developed in different ways: Electro-Absorption Modulators (EAM) are very compact but a single device operates in a limited wavelength range only and the chirp is difficult to adjust. Mach-Zehnder Interferometer (MZI) modulators can be used for (standard) on-off keying (like EAM), but they are also suited for alternative, more advanced modulation formats like Differential Phase Shift Keying (DPSK), which is attracting high current interest. Mach-Zehnder modulators in LiNbO₃ have particularly low insertion loss and operate over a wide wavelength range, however, commercial devices normally require 5 V peak-to-peak driving voltage (V_{pp}) and as a consequence rather expensive driving electronics. MZ modulators in GaInAsP/InP, on the other hand, offer a large operation wavelength range, low or adjustable chirp and about 2 V_{pp}. 40 Gbit/s MZI modulators in GaInAsP/InP are under current development in various laboratories. One design, which relies on travelling-wave electrodes (TWE) is shown in Fig. 5.

![Fig. 5. Design of Mach-Zehnder Interferometer modulator suited for 40 Gbit/s (and higher bit rates)](image)

Other characteristics of the MZI modulators are a Multi-Quantum Well (MQW) layer structure, air bridges connecting the TWEs and the waveguide ridges, and integrated tapers for efficient fibre-chip coupling. > 40 GHz bandwidth has already been demonstrated and with appropriate refinements the design chosen should enable 80 and even 160 Gbit/s modulation speed.

6. Picosecond pulse source OEIC

At present it is difficult to predict at what time (or even whether at all) single channel bit rates as high as 160 Gbit/s will find applications in fibre optic systems. Nevertheless such systems are investigated in various R&D labs. Modulators enabling direct modulation at 160 Gbit/s are not available at present, but OTDM is a technique enabling such a high channel bit rate. The principle of OTDM is illustrated in Fig. 6. According to Fig. 6 OTDM relies on the time domain interleaving of short optical pulses, the basic repetition rate could
either be 10 or 40 Gbit/s, the modulators in the different delay lines operate at the same bit rate, and the pulse width should be in the order of about 1 to 2 ps, and such pulse sources are a current research topic.

The most widely chosen approach for such pulse sources is that of a mode-locked laser. In order to assure operation at exactly the systems frequency the devices must be designed for external locking. A corresponding design is shown in Fig. 7, which illustrates a monolithically-integrated four-section Distributed Bragg Reflector (DBR) laser [7].

Characteristics of the ps-OEIC are: 2.2±0.4 ps pulse width, 220±40 fs timing jitter (measurement range: 100 Hz – 10 MHz), 0.34…0.50 time-bandwidth product, >1 mW output power into the optical fibre, about 5 nm tuning of the emission wavelength. The repetition frequency of the pulse source can be locked to an external frequency provided the free running repetition frequency is close enough to the external locking frequency, and this can be assured by an appropriate cavity length. Fig. 8 illustrates the locking bandwidth of a pulse source, which exhibits −550 MHz repetition rate tuning (by 70 mA gain current variation). In order to exactly match any given systems (repetition) frequency, the cavity length variation must not exceed ±2 µm. Such an accuracy is very demanding but can be achieved if the location of the cleaved facet is determined by lithographic means (with appropriate processing).
7. High speed photodetectors

A particularly promising concept for ultra-high speed photodetectors is a pin photo diode evanescently coupled to a dielectric waveguide, where a high fibre-chip coupling efficiency is obtained by monolithically integrating a spot size converter [8]. The basic concept has recently been extended to a balanced receiver comprising two waveguide integrated photodiodes, which are electrically connected in an anti-parallel configuration (cf. Fig. 9). As a consequence the photo currents are subtracted directly on chip, which improves the RF performance at high frequencies. A responsivity of 0.35 A/W for each photodiode has been measured with less than 0.6 dB polarisation dependent loss [9]. The photodiodes exhibit 40 GHz bandwidth and the frequency characteristics of both devices agree within 0.5 dB (cf. Fig. 10). The balanced receiver is particularly suited as a detector for DPSK.

8. Self-pulsating lasers

Multi-section DFB lasers can be designed in such a way that they exhibit self-pulsations even if they are dc-driven. If an external optical signal is fed into the self-pulsating laser (SPL), the SPL locks to the bit rate of the external signal and the device can thus be used for all-optical clock recovery. This is particularly attractive for high bit rates (40 Gbit/s and beyond), and SPL have consequently been investigated for more than a
decade and have been used more recently successfully in transmission experiments [10]. Fig. 11 compares the frequency spectrum of an SPL in the free running and in the locked state and thus illustrates the locking phenomenon.

![Figure 11](image_url)

**Fig. 11.** Frequency spectra of self-pulsating laser in free-running and locked state [10]

### 9. Monolithic integration trends

Monolithic integration has been considered for quite a while an attractive strategy to reduce mounting effort, reduce coupling losses, increase reliability and reduce cost. However, successful monolithic integrations depend in general on a number of preconditions. The most important are: the devices to be integrated monolithically should have the same (or rather similar) layer structure (i.e. the total processing effort of the integrated device should not be much larger than the processing effort for the individual subcomponents), and the design should lend itself to a compact architecture, for example by allowing an in-line geometry.

One example of successful monolithic integration are multi-wavelength sources (with a variety of architectures) and designed in such a way that one laser operates at a time. Other successful integrations are that of a laser + EAM, or a (widely tunable) laser + EAM + SOA + monitor photodiode (cf. Sec. 4), or interferometric structures comprising several SOAs serving as all-optical wavelength converters or as OTDM demultiplexers.

On the other hand, if OptoElectronic ICs (OEICs) comprise a number of dielectric waveguides including waveguide bends (with rather large bend radii in order to avoid excessive bending losses) such OEICs tend to become large, while the area of the active devices covers a small fraction of the OEIC only. The overall OEIC cost is essentially proportional to the total chip area and thus such OEICs become expensive and cannot compete successfully with hybrid solutions. Finally, if lasers and detectors are integrated monolithically close to each other and are expected to operate at the same time, the spontaneous laser emission tends to spoil the photodiode dark current. The only solution is increasing their separation, but this leads once again to an unacceptable large total chip area.

As a consequence optoelectronic monolithic integration has made progress in recent years, but the number of different components integrated on a single chip is still rather low, and the corresponding discrepancy between the degree of electronic and optoelectronic integration is very likely to remain for quite a while.
A completely new class of semiconductor-based OE devices are so-called "Photonic Crystals (PC)" or "Photonic Bandgap" structures based on two- (or even three-) dimensional periodic patterns with an order of magnitude smaller geometrical device dimensions than conventional OEICs. PCs offer the following promising characteristics: several 10 µm subcomponent size, low-loss light guiding around sharp corners, extremely high wavelength dispersion, omni-directional reflectivity under specific conditions. In GaInAsP/InP novel filter and SOA concepts are under current development, ultra short optical field transformers have already been realized, and there is the expectation that PC-based (sub)components might enable particularly compact monolithic integrated structures, and that corresponding devices might enter the market in the next few years. Nevertheless, there are still a significant number of conceptual and technological challenging tasks, which have to be completed before PC-based chips will become a commercial commodity.

References

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