DWDM lasers fashion networks of the future

Component manufacturers are leveraging their know-how in advanced semiconductors, optoelectronics and packaging as they race to deliver the next generation of high-speed lasers to bandwidth-hungry system vendors. Olof Sahlén reports.

IT‘S TAKEN LESS than two years for dense wavelength division multiplexing (DWDM) to transform the economics of bandwidth provision. Network operators dragging their heels in the slow lane of the information superhighway no longer have to resort to the time-consuming and costly business of new fibre deployment. Instead, they can scale up their capacities by using DWDM to transport dozens of multigigabit traffic streams simultaneously down a single optical pipe.

The latest DWDM systems represent a truly inipressive marriage of optoelectronic and electronic engineering, characterized by numerous wavelengths (from 16 channels up to 100 and beyond); channel separations as small as 100 GHz (0.8 nm) or 50 GHz (0.4 nm); channel data rates from 155 Mbit/s to 10 Gbitls; and long transmission spans (up to 600 km or more, largely on standard singlemode fibre).

Such exacting specifications are possible thanks largely to advances in transmitter technology, specifically the advent of highspeed semiconductor lasers with well controlled spectrum under modulation. For the systems manufacturers, the most cost-effective transmitter option is the directly modulated distributed-feedback (DFB) laser, particularly at lower bit rates (155 and 622 Mbit/s channel speeds), but also for 2.5 Gbit/s over shorter distances (up to 100 km).

Unfortunately, directly modulated devices exhibit unacceptable chirp (wavelength drift) as a result of relaxation oscillations during modulation — a feature that makes them unsuitable for long transmission distances. They are also far from ideal for generating signals with a high extinction ratio (greater than 10 dB) at high bit rates.

Because of these drawbacks, externally modulated devices have now emerged as the technology of choice for DWDM transmitters operating at line rates of 2.5 and 10 Gbit/s. There are two main strategies:

- **Continuous-wave (CW) DFB lasers with separate Mach—Zehnder modulators (either $LiNbO_3$ or InP).** In these devices, the separation of the light-generation and inodulation functions allows separate optimization of the optical modulator and the optical oscil lator. It‘s also worth noting that the modulators deliver excellent chirp performance.

A complex business: the fabrication of DFB-EA transmitters is a multistage process involving the sequential definition of the laser, grating and modulator structures.

- **CW DFB lasers monolithically integrated with electro-absorption (EA) modulators.**

Although fabricated using processes similar to those for directly modulated DFB lasers, DFB-EA sources ensure significantly better chirp and extinction-ratio specifications. The lasers also combine small size, low drive voltage and lower total cost compared with traditional external modulation.

The following survey draws on my experience at Ericsson Microelectronics, where one of our strengths is the development and manufacture of discrete DFB and DFB-EA lasers (as well as complete modules with driver and control electronics).

DFB-EA laser fabrication

In the DFB-EA design, the laser is optimized for CW operation (in terms of linewidth, sidemode suppression ratio, singlemode yield and output power), while an electrical, high-bit-rate modulation signal changes the absorption of the modulator waveguide.

The modulator waveguide, a p—i—n diode, is fabricated from a series of thin semiconductor layers with a slightly larger energy bandgap than the photon energy of the DFB laser output. As a result, the modulator is (almost) transparent at 0 V,

The application of a negative voltage, however, induces a large electric field in the modulator, resulting in increased absorption and high optical loss. At the same time the electric field also gives rise to chirp by triggering a slight change in the modulator‘s refractive index. Exactly how much the refractive index alters depends critically on the semiconductor layer design and on the so-called detuning (the energy difference between the impinging laser photons and the modulator‘s bandgap).

Using this design template, manufacturers have now devised several different ways to realize DFB-EA devices. The structure shown in figure 1, for example, exploits the InP/InGaAsP material system and is fabricated using a technique called metal—organic vapour-phase epitaxy. The first stage — deposition of the DFB structure — is followed by the writing of the grating layer adjacent to the laser‘s active region. (At Ericsson we use electron-beam lithography to fashion the grating, though it‘s also possible to employ holographic methods based on the interference of two laser beams.)

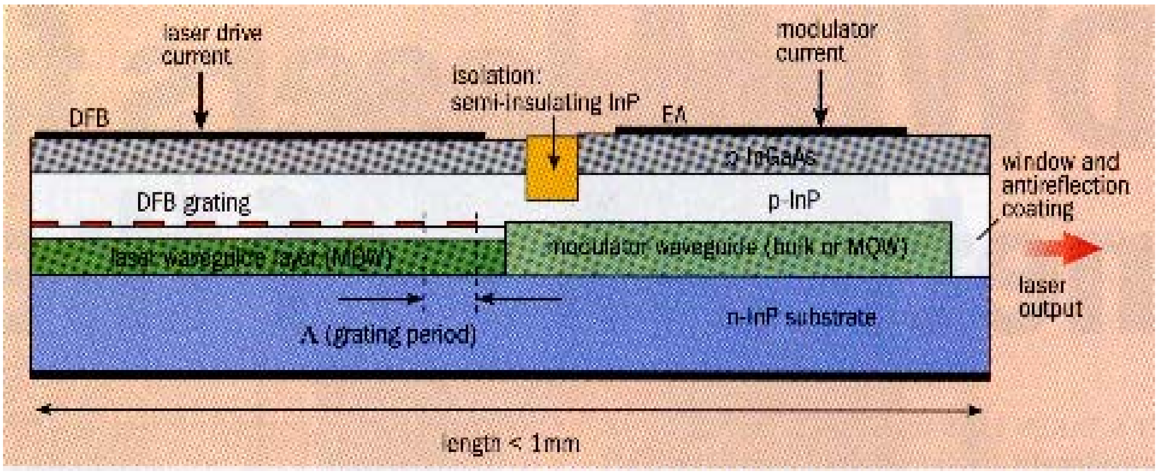

Fig 1 Schematic of the monolithic DFB-EA chip viewed as a longitudinal cut through the 1 µm wide optical waveguide. The modulator waveguide terminates to the left of the cleaved chip facet to form a window structure together with the antireflection coating on the chip facet.

The grating period (the pitch of alternating high- and low-refractive-index regions) determines the output wavelength of the DFB laser. In the simplest case, the wavelength equals $2n\Lambda$, where n is the effective refractive index of the laser waveguide and Λ is the grating period. What this means is that component makers can fabricate lasers with different wavelengths on a single InP wafer. For example, a 1550 nm laser with an effective index of 3.25 needs a grating period of 238.5 nm. To make adjacent lasers with wavelength differences of 0.4 nm (50 GHz channel separation), the manufaeturer thus has to adjust the grating period by about 0.06 nm in each case (if dispersion of the effective refractive index is neglected).

Nevertheless, things are not as straightforward as they first appear. That‘s because the absolute accuracy of the DFB laser wavelength cannot be controlled to better than within 1 nm using the grating on its own. As a consequence, the clips have to be finetuned to the exact system channel wavelength (to within 0.01 nm) with the help of active temperature control (a thermoelectric cooler and a thermistor).

Once the grating is written, superfluous laser material is etched away und regrowth of the modulator layer sequence takes place. Usually, both the laser und modulator waveguides include multiple-quantum-well regions (ultra-thin layers, each less than 10 nm thick, of alternating low- and highbandgap materials). The exact design of these structures - material composition, number of layers, thickness and strain - determines the detailed chirp and extinction-ratio performance of the transmitters.

A further etching process defines the approximately 1 µm wide optical waveguide. This is followed by the regrowth of semi-insulating (iron-doped) InP around the optical waveguide, and also between the laser and the modulator, to ensure high electrical isolation. The final steps in the fabrication cycle involve the growth of p-doped InP und InGaAs layers and the formation of electrical contacts through metallization.

The package design — und there are many variants — is as important as the chip in determining the overall cost performance specification of a DWDM transmitter. Figure 2 shows a schematic view into the butterfly package of one implementation where the chip (DFB or DFB-EA) is mounted together with a temperature sensor on a subcarrier. Behind the subcarrier sits a monitor-diode providing automatic power control; in front of it there‘s an optical System comprising a collimating lens, an optical isolator and a focusing lens. The lenses image the optical spot from the laser chip (approximate diameter 1 µm) onto the optical fibre (spot diameter 10 µm). The laser subcarrier, monitor diode, coupling optics and optical fibre all mount on a common mechanical support.

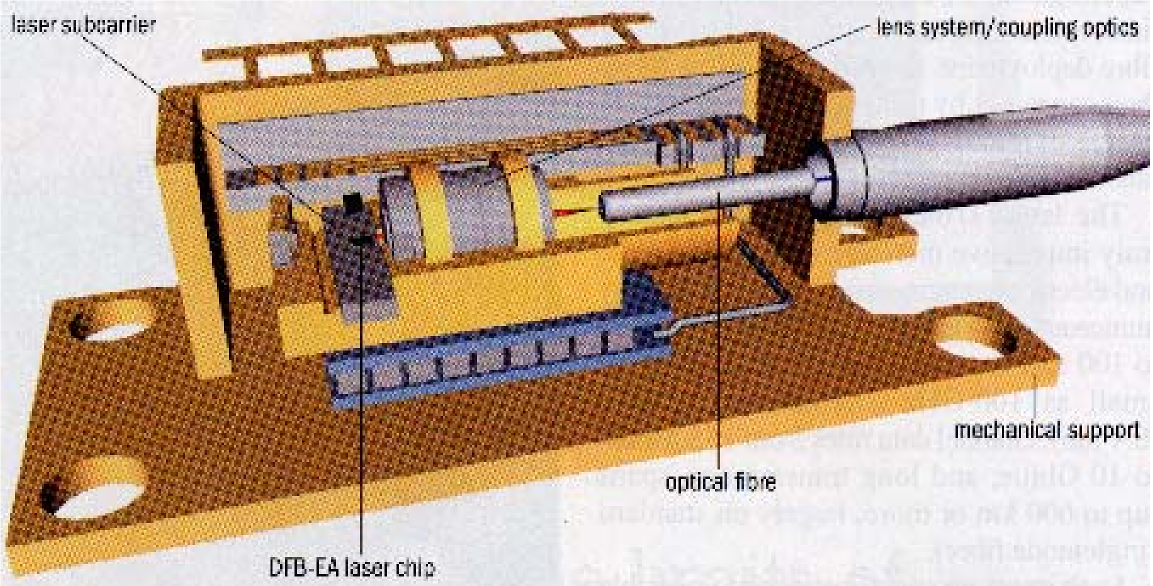

Fig. 2: Schematic of the DFB-EA package. The chip (black, with red-light cone) mounts onto a subcarrier (which includes some impedance matching and a temperature sensor). The laser, lenses, isolator and fibre ferrule are all-temperature controlled by a thermoelectric cooler and a thermistor.

Beneath the mechanical support is a thermoelectric cooler that provides temperature control of the DFB-EA chip (together with the temperature sensor). Since the wavelength of a DFB laser depends on the chip temperature (roughly 0.08 nm/K), the temperature needs to be stabilized to a fraction of a degree kelvin. Not shown on figure 2 are the microwave connection (located towards the viewer) or the circuitry used to match the high-impedance, capacative load of the modulator to the 50 Ω input transmission line. The microwave feeds are leads in the case of 2.5 Gbit/s transmitters and coaxial connectors in the case of 10 Gbit/s devices.

Where next for lasers?

Right now, laser manufacturers are building on all of this know-how in materials, optoelectronics and packaging to fashion next-generation transmitters that will meet equipment vendors‘ and operators‘ demands for higher-speed optical networks.

One of their priorities is the commercialization of L-band lasers that generate light between 1560 and 1620 nm. When used in tandem with L-band optical amplifiers, which are already being shipped by several vendors, these lasers will enable DWDM systems to pipe more than 1 Tbit/s of data down a single optical fibre.

Another area receiving lots of attention is the modulator‘s multiple-quantum-well design, which, when optimized, will guarantee longer transmission distances from DWDM lasers. “Ideal“ modulators can achieve distances of the order of 100 km at 10 Gbit/s and 1600 km at 2.5 Gbit/s (if the DFB laser linewidth is minimized to avoid phase-noise to amplitude-noise conversion on the dispersive fibre).

In the medium- to long-term, the possibilities become even more intriguing. Intense R&D is already under way on 40 Gbit/s DWDM systems and devices, especially on critical issues such as polarization-mode dispersion, chromatic dispersion and the choice of modulation format. Progress on transmitter components has been rapid, with several groups recently publishing details of standalone EA modulators with more than 50 GHz bandwidth. Here at Ericsson, we have demonstrated an integrated DFB-EA chip with close to 35 GHz bandwidth, thus confirming that our DFB-EA technology is also compatible with 40 Gbit/s.

Beyond the push for more gigabits per second and more distance, there is also a desire to incorporate greater functionality within the DWDM laser package itself. One strategy is to include the drive electronics in high-bit-rate (10 Gbit/s) devices; after all, it is easier to achieve good microwave matching between the optoelectronic device and the electronics if they are close to each other. Several vendors have also unveiled prototypes that include the wavelength-locking or referencing units in the laser package, a feature that will be particularly important if the DWDM wavelength separation decreases below 50 GHz.

The final piece in the R&D jigsaw is the wavelength-tunable laser. The simplest way to make such a device involves the thermal tuning of a DFB laser, providing a spectral spread between 3 to 5 nm. It‘s also possible to widen the tuning range by integrating multiple DFB lasers onto the same chip (FibreSystems April 1999 p113).

Another concept is to exploit electronic tuning of grating and phase sections — for example, the classical distributed Bragg reflector (DBR) laser. Some manufacturers have used advanced variants of DBR-like lasers to notch up tuning ranges of 100 nm, though there‘s still plenty of work to do before they can guarantee consistent tuning properties over a 25-year lifetime.

Despite the fact that tunable lasers are still at the prototype stage, the devices are widely touted as ideal stand-by parts for today‘s increasingly complex DWDM systems. If a fixed-wavelength laser fails, for example, a tunable source could simply replace the missing channel, thereby reducing the amount of inventory that sits on the shelf doing nothing. And the applications are unlikely to end here, with some analysts predicting that tunable devices could very well become essential building blocks in the wavelength routers and protection switches of a transparent, all-optical network.

Performance trade-offs and custom lasers

It is possible, within strict limits, to tailor the exact cost:performance of a DFB-EA laser to individual customer requirements. Among the trade-offs are optical output power versus extinction ratio and chirp, and modulation bandwidth versus extinction ratio and optical output power.

The extinction ratio, for example, increases as the modulator length increases (but so too do he capacitance and insertion loss). Similarly, to make a device with good chirp performance, the modulator must have a slightly larger insertion loss (smaller detuning between the lasing wavelength and the bandgap of the modulator).

Figure 3 shows the measured chirp and optical power from a 10 Gbit/s DFB-EA laser during modulation. The modulator has a negative chirp parameter, which means that the first flank of a “mark“ pulse is red-shifted and the falling flank is blue-shifted. This leads to initial pulse compression, which is favourable for bridging long distances on standard singlemode fibre.

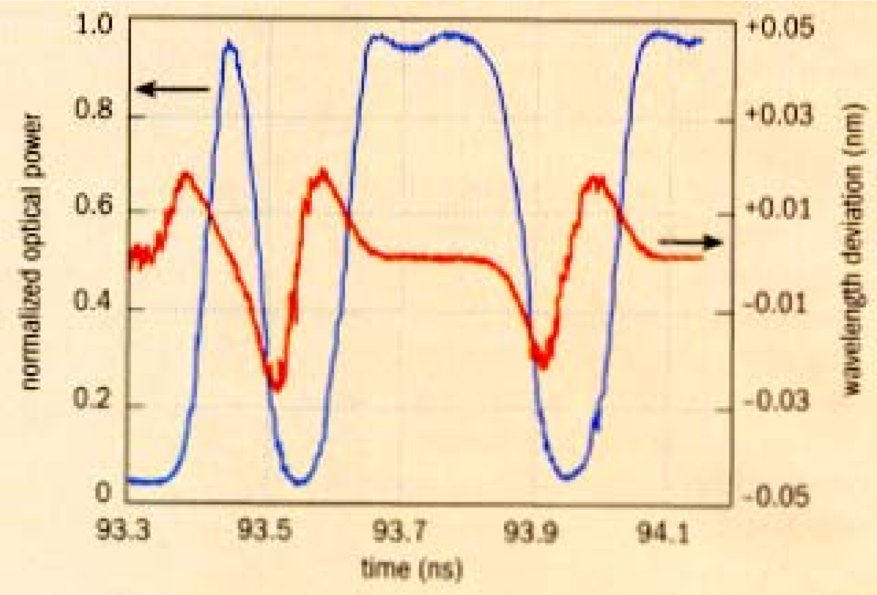

Fig. 3: Optical power (blne curve) and wavelength ex~ursion fred) from a 10 Gbit/s DF~-EA lasertransmitter. In this example the electrical drive signal is about 1.9 V peak to peak.

Typical performance parameters of DFB-EA laser products currently available from Ericsson Microelectronics include:

- Mean modulated optical output power of —3 dBm or more in the fibre pigtail.
- Transmission distances up to 60 km at 10 Gbit/s and up to600km at 2.5Gbit/s on standard singlemode fibre without dispersion compensation.
- A dynamic extinction ratio of 10 dB or more during 2.5 or 10 Gbit/s modulation with a 2 V peak-to-peak driving signal. A arger driver amplitude provides a larger extinction ratio.
- Laser threshold currents of about 10 mA: the DFB lasers have side-mode-suppression ratios higher than 35 dB.
- Small-signal modulation bandwidths typically better than 50 Hz for 2.5 Gbit/s and better than 12 GHz for 10 Gbit/s. The bandwidth is package limited; the chip has a bandwidth of 20 GHz.

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