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Semiconductor Devices for Fiber Optic Communication Systems

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Abstract - We review the state-of-the-art of heterojunction-based integrated circuit technologies that have potential applications for time division multiplexing (TDM) and wavelength division multiplexing (WDM).

I. INTRODUCTION

In the last few years, the evolution of large capacity fiber optic networks has been basically progressing in two directions: high-speed time division multiplexing (TDM) and wavelength division multiplexing (WDM).

In TDM systems, high-speed optoelectronic processing exists between origin and destination of the optical signals. Some of the advantages of TDM over all optical devices include compact size, lower cost, high reliability and versatility in the operation. However the optimum performance or bit-rate depends on the speed of each individual circuit, which is primarily limited by the semiconductor technology used. In general, a TDM system has an economical advantage if high-speed electronics components are available.

On the other hand, WDM systems have become the popular solution for the bandwidth crunch. With multiple wavelengths, WDM systems provide aggregated speeds much higher than those obtained for single channel TDM.

At lower individual channel rates, there are fewer demands on the electronic components and easier chromatic dispersion compensation due to minimal fiber non-linear effects. Nevertheless, upgrading with additional wavelengths means also closer channel spacing, which is a challenge.

With the development of broadband erbium doped fiber amplifiers (EDFA), simultaneous amplification for both high-speed TDM and WDM signals became possible. Presently, most of the optical networks have a hybrid mixture of TDM and WDM technologies with fiber dispersion management and depending on the architecture, may include interfaces with high-speed physical layer electronics [1].

In this paper, the state-of-the-art of integrated circuit technologies will be reviewed, focusing mainly on heterostructure transistors that have potential applications for lightwave systems.

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II. COMPONENTS AND REQUIREMENTS

The key element in optical communications, responsible for the translation between the optical and electronic domain is the transceiver. Figure 1 displays a complete optical transceiver. On the upper part of the transceiver schematic, it is the transmitter where streams of digital data are assembled into a single high data rate serial stream, then encoding this information on the output of a *laser*. The *multiplexer* performs the multiplex operation while may encode the data or add error checking and framing bits. The number of digital input channels required by the multiplexer may range from 4 to 16. With the increased number of channels, the complexity and total power dissipation becomes an important factor in deciding which technology will be suitable for the transceiver.

The output of the multiplexer is delivered to the laser driver circuitry. The *driver* module modulates the optical signal and establishes electronic and thermal bias conditions required for stable operation. To date, for high speed rates, the *modulator* and laser optical power-control circuits have not been integrated but rather are separate entities. For rates higher than 10 Gb/s, it is very difficult to implement directly modulated laser (except for short links) because of impairments such as chirp so external modulation technologies using waveguide electrooptic modulators have been widely adopted. Typically, the modulator driver circuit has multiple amplifier stages with single or differential outputs with broadband operation over several decades in the frequency domain. For example, the lithium niobate ($LiNbO_3$) technology requires about 5 to 7V while semiconductor-based modulators (either bulk or electron absorption type) need only half of that (3-4V) for operation.

On the lower part of the transceiver schematic, depicted in Figure 1, is the receiver side. The first electronic components are the *transimpedance amplifier* (TIA) and main *amplifier*. Basically the TIA converts the photocurrent output of the photodetector to a voltage as large as possible with an absolute minimum electrical noise. This particular component requires broad bandwidth, low noise and high gain. The main amplifier converts the TIA output to a suitable lever for signal processing. Either gain control or high gain limiting configuration needs to be implemented in the design of the main amplifier, since the output of the TIA can span a wide range of amplitude values, because of the difference in laser output, repeater spacing and detector sensitivity.

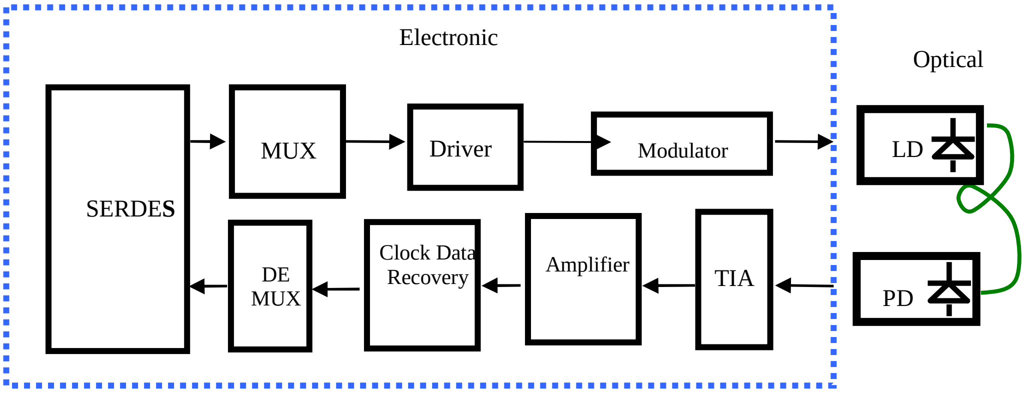

Figure 1: Diagram of a high-speed optical transponder.

Following the main amplifier, the components include functions for reshaping, time extraction and signal regeneration (the so-called 3R for reshaping, retiming and regenerating). The *timing circuit* has to regenerate the system clock and distinguish or restore even a noise-obscured signal between digital ONE and ZERO.

The *clock recovery* module depends on the data format and is a mixed signal circuit with a voltage-controlled oscillator (VCO) or phase locking-feedback loop (PLL) that operates at the data rate. The data recovery usually involves a decision circuit, basically a toggle circuit (D-flip-flop) with amplifier stages for data and clock input data. The operating speed in this case is limited by the maximum toggle speed of the logical gate that as discussed in the next session is related to the individual transistor technology. The output of the data and clock recovery module feeds the multiplexing module basically digital referred as the *demultiplexer*.

The data processing, the serial/deserializer (*SERDES*), is the physical layer interface with standards for data format providing the critical connection between the local electronic traffic and the high speed components. The SERDES module is also developed for framer and forward error correction functions.

As discussed, most of the components are based on integrated circuit technologies, with the exception of the retiming circuit. However the speed limitation can be translated to the semiconductor device technology as discussed below.

III. DEVICE TECHNOLOGY AND PERFORMANCE LIMITATIONS

From a purely optical point-of-view, one could calculate the maximum amount of information that can be transmitted over optical fiber, therefore implying that lightwave technology can yield robust, long-term and scalable communications networks. Theoretically, it is possible to send 100 terabits of information, or roughly 20 billion one-page e-mails, simultaneously per strand of fiber. So, it seems reasonable to expect that 100 Gb/s or even higher data rate systems will be part of our lives in the near future [2]. Even for WDM systems, the ultimate aggregated capacity and deployment will probably relay to availability of the electronic components and their performance [3]. A variety of factors determine the ultimate circuit speed but mostly of all is the intrinsic device speed [4]. Figure 2 summarizes the evolution of the gate delay or toggle frequency among the different semiconductor technologies.

For 10 Gb/s applications, the state-of-the-art semiconductor technologies available today include Si, CMOS, SiGe, GaAs and InP transistors. To compare these technologies some figures-of-merit are directly related to the individual transistor technology and semiconductor material combination yielding the final speed for a given electronic circuit. For example, toggle frequencies or gate switching times are related to digital circuits like frequency dividers, multiplexers and demultiplexers while the unity power gain (related to the maximum frequency of oscillation, fmax) is more suitable to predict analog circuits like amplifiers.

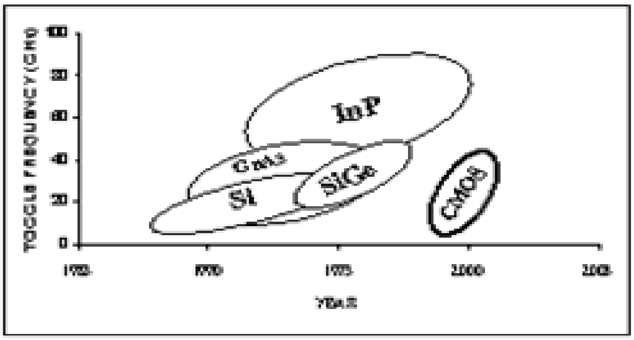

Figure 2: Evolution of the toggle frequency (or also gate delay) for the major semiconductor technologies during the last 20 years.

Another figure-of-merit is the breakdown voltage of the transistors variation with the RF performance. Specifically for optical modulators drivers, an integrated circuit that requires large transistor breakdown, as discussed in the previous session. Figure 3 summarizes the relationship between reported values for the different semiconductor technologies [4-11].

With short gate lengths, field effect transistors (FETs) have higher speed for compound semiconductor materials than for silicon because of higher electron mobility leading to higher device transconductance. Among the compound semiconductor materials, InP-based heterojunction FETs (HFETs), for a given gate length, have higher switching frequency than those with GaAs-based HFETs, because of the larger electron velocity of that material system. However, incumbent wide band gap materials like GaN-based HFETs could provide even higher gain amplifiers.

In the case of bipolar transistors, the silicon bipolar has remained very competitive in high speed with the super self-aligned but also with inclusion of SiGe heterojunction bipolar transistors (HBTs). The wide bandgap emitter material in HBTs allows the transistor to have higher current gain by limiting the back injection of holes back into the emitter. With a higher base doping, lower base resistances and thinner base layers, the high speed is comparable to those obtained for GaAs-based HBTs without the surface recombination handicap.

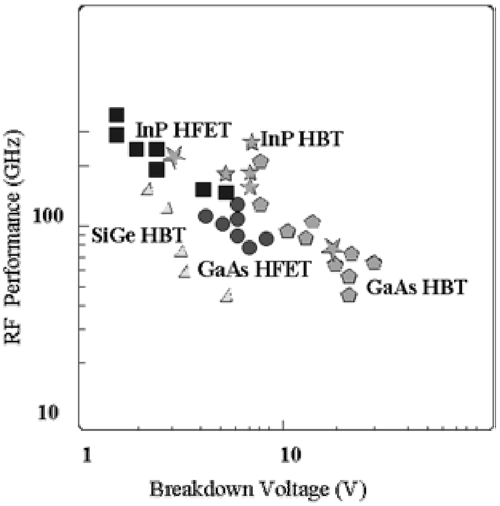

Figure 3: Microwave performance variation with breakdown voltage for different technologies and transistors, expanded from [4].

Recently, with advanced epitaxial growth more exotic materials like Sb-based transistors associated with high resistivity substrate promise to yield even higher switching speeds at lower power dissipation [12,13].

IV. CONCLUSION

The major limitations when comparing complex technologies and materials are primarily related to the differences in the device and materials development stages and circuit complexity. From the perspective of the end user of those specialized circuits, the performance also needs to include lower power dissipation, lower cost and more compact chips. Optical communications systems as end user will certainly benefit independent of the technology that eventually dominates.

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