Electronics and Optical Communiqué Bottlenecks by 2007

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Abstract:- Communication bandwidth has become limited to 40GHz due to electronic switching speed limitation. Available devices operate at 40GHz and beyond are just prototype models. Even the 40-50GHz switching devices are under constant investigation. Nanotechnology has failed to cope with ever increasing electronic switching speed demands. Probably we require picotechnology now and femtotechnology in next few years to accelerate the switching speed limits to THz regime through novel photonic or light switches yet to be explored. Optical fibres offer greater than 25THz bandwidth that can not be utilized due to obvious reasons. Data communication rate was increased to a few THz level through OTDM/DWDM techniques but EDFA noise, bandwidth-distance product and Stimulated Raman Scattering (SRS) limitations do not allow to further increase multiple laser wavelengths carriers multiplexing without proportional increase in electronic switching speeds. This paper reviews basics of the electronic and optical communication limitations and proposes thin film integrated optics based photonic strategies to overcome the impounding bottlenecks.

Key-Words: Electronic devices, Photonic devices, Optoelectronics, Electronic bottlenecks

1. Introduction

For very high speed OTDM transmission, it becomes essential to generate picosecond transform limited pulses at repetition rates of 10 to 40 GHz. High repetition rate has to be tuneable and controllable to permit synchronization with other signals. Oscillation wavelength should be tuneable to optimize picosecond pulse transmission. The fastest electronic devices have a time resolution of about 10 picoseconds. As a result, one must use the femtosecond pulse to measure itself, what is commonly called an optical autocorrelator. Femtosecond pulses are required for making motion pictures of atomic and molecular vibrations, bond breaking and making studies in chemistry and biological studies. Any object moving at 1000 km/s speed can be pictured at 0.1Å resolution using only attosecond pulses [1]. Pulses of attoseconds were generated to study the motion of electrons around the nucleus of a neon atom [2]. Theoretical basis for Zeptosecond and Yoctosecond pulses are topics of the current interest to realize yoctosecond events [3]. Typical applications may include femtochemistry, medical imaging, micromaching and high resolution motion studies [4]. Of course ultrafast optics can help overcome electronic and fibre optic communication bottlenecks but it still needs to develop its muscles to cope with natural events such as “the mean lifetime of the top quark, inferred to be about 0.4 yoctosecond” [5] and few other particles having mean lifetime even shorter than above. The ultimate limits of time, energy and space are beyond the human grasp. At frontier units such as 10^{-45} sec (Rintosecond), 10^{45} watts (Rintawatt) and 10^{45} km the time, energy and space become intertwined and matter becomes energy due to dimensional orders comparable to Plank’s time. However, it is still interesting to produce rs laser pulses to realize ultimate speed limits [6].

2. Electronics Bottlenecks

Strictly speaking 40 GHz is the bottleneck of available electronic devices. However, 50-100 GHz electronic devices are under intensive research [7]. Electrical Time Division Multiplexing (ETDM) yet limited to bellow 50 GHz. High speed transistors offer 100 Gbps repetition rates but when signal λ approaches circuit chip size the parasitic effects worsen IC design. Standard single mode optical fibre may offer more than 25 THz bandwidth. Theoretically 25x1012/40x109 = 625 lines of 40 Gbps can be multiplexed. Present data rates in practice are 2.5, 10 and 40 Gbps. Optical Time Division Multiplexing (OTDM) can exceed 10 Tbps barrier. Electroabsorption modulator, integrated with 200µm size DFB laser, can operate at 10 Gbps speeds. Electrooptic modulator, integrated with DFB laser at 3-5 cm size, can operate at even higher speeds. Polymer modulator unlike EO modulator requires low drive voltage but operates at lower speed. Semiconductor (III-V) modulators can be integrated with other devices such as DFB lasers and photodiodes. Transmitters and receivers require high speed electronics not only for modulator drivers and photoreceivers but also for clock recovery and decision making. Currently electronic available modulators can operate at 40 Gbps using Si-Ge, GaAs and InP based materials. Fibre optic transmission capacity compared to electronic processing speed is illustrated in Fig.1.

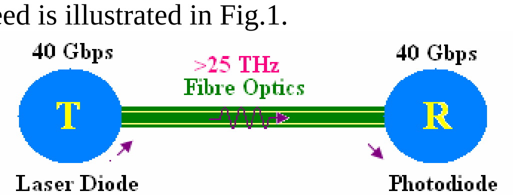

Fig.1 Fibre transmission and electronic processing bandwidth limitations

Eelectro-absorption (EA) modulator allows controlling the intensity of a laser beam via several tens GHz signal generator output clock train. Compared with electro-optic (kV) modulator, EA modulator can operate with much lower voltages (3-7 V), which makes it useful device for optical fibre communication. A convenient feature is that an EA modulator can be integrated with a distributed feedback laser diode on a single chip to form a data transmitter in the form of a photonic integrated circuit. Compared with directly modulating the laser diode, one can in this way obtain a higher bandwidth and reduced chirp [8]. An integrated DFB laser and EA modulator are shown in Fig.2. Limiting factors for electronic IC for 100 Gbps and faster operation include InP and Sb based HBT and HEMT with low parasitic chips. Present bandwidth demand in optical communication is 100 Gbps that is increasing day by day. Such high speed system cannot be realized, without introducing ultrafast (all-optical devices), since the existing optoelectronic and electronic devices and integrated circuits are unable to function at a bit rate exceeding 100 Gbps even in labs.

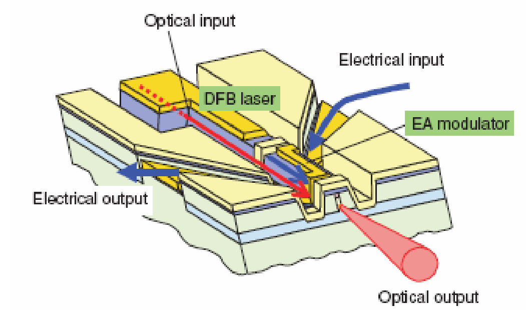

Fig.2 EA/DFB laser modulator (Courtesy of NTT: Copyright©2003 NTT)

All-optical devices based on completely new principles have to be explored. Ultrafast devices require a still higher repetition rate and lower power consumption. Recent developments include mode-locked lasers and a variety of all-optical switching based on different principles such as Mach–Zehnder interferometer structures, spin relaxation, inter-subband transitions, and ultrafast absorption recovery in organic thin films and semiconductor quantum dots. However, some of the recent developments have shown potential capability of materials to deal with data rates of 0.5 to 1 Tbps as illustrated in Fig.3 [9].

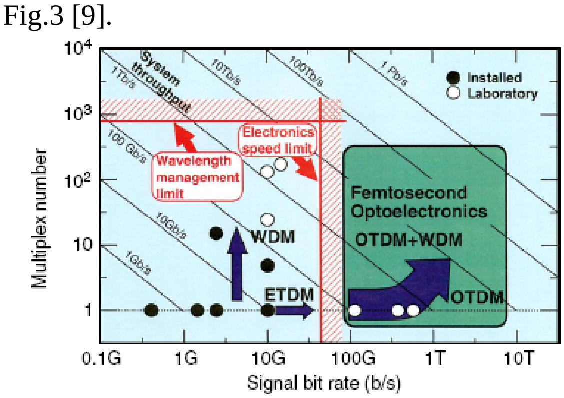

Fig.3 State of art of optical communication technology (Copyright by O.Wada NJP (ref.9))

There are considerable challenges to achieve data rates beyond 100 Gbps. High speed electronic circuits are extremely difficult to build. Two major issues may include the design of the electronic processing elements for packet forwarding/classification and opto-electronic devices for physical transport of data through switches/routers using application-specific integrated circuits (ASICs) that are designed with CMOS technology that is based on a misleading Moore's Law [10]. International Technology Roadmap for Semiconductors (ITRS) predicts the possibility of manufacturing complex chips down to 50 nm feature size but production of practical mask and exposure systems (lithography) below 50 nm feature size will be a major bottleneck for such chips. Available electronic switching speeds are shown in Table 1.

Table 1 HEMT/HBT electronic devices speed limitations

Device/Speed	FET/HEMT (Gbps)		HBT (Gbps)		
Integrated Circuit (IC)	GaAs	InP	SiGe	GaAs	InP
Multiplexer	45	100	50	60	50
Demultiplexer	40	50	60	60	50
Modulator Driver	40	40-50	50	40	40

Light absorbed in the depletion region or the intrinsic region generates electron-hole pairs, most of which contribute to a photocurrent. Photodiodes operated in photovoltaic mode, like a solar cell, generate a voltage which can be measured. However, the dependence of this voltage on the light power is rather nonlinear and the dynamic range is quite small. Also, the maximum speed is not achieved. However, photodiodes operated in photoconductive mode require large reverse voltage. At higher voltage it tends to make the response faster but also increases the heating of the device. Typical photodiode materials include silicon (low dark current, high speed, best sensitivity around 800-900 nm), germanium (high dark current, slow speed due to large parasitic capacity, best sensitivity around 1400-1500 nm, good for optical communication) and indium gallium arsenide (expensive, low dark current, high speed, best sensitivity around 1300-1600 nm, good for optical communication). As the holes are slower than electrons therefore present trend is to improve response time using uni-travelling carrier wave (UTC) photodiodes [7].

UTC photodiode is not RC limited. However, the transit time of the charge carriers in the device is limiting its bandwidth. UTC photodiodes have recently been introduced and seem to be the next generation working horse if sub nm devices become possible [11]. On the sending side electro-absorption modulated DFB laser chip is the highest speed transmitter [12].

Pure silicon based devices are in general elusive, but Luxtera has developed a 10 Gbps silicon transceiver chips. Intel ultimate silicon laser based holy grail capable of modulating 25 silicon laser output using 25 optical modulators each at 40 Gbps (still a challenge) for 1 Tbps speed employing hybrid evanescent silicon waveguide lasers and novel silicon modulators is shown in Fig. 4 [13].

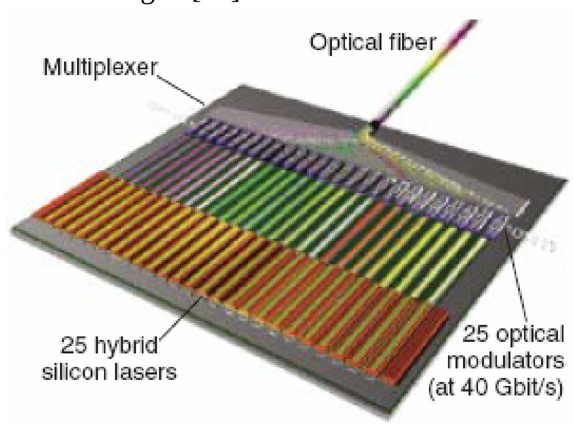

Fig.4 Intel's holy grail for 1 Tbps optical interconnect (Courtesy of Intel and LFW (Ref.13))

Well femtosecond streak camera (C6138), 20 GHz scopes (agilent) and 40 GHz signal generators are available in market from many vendors. The eventuality of the present research is to reduce transit time between electrodes for photodetectors and increase repetition rate of electroabsorption DFB laser to increase switching speed. Typical Hamamatsu 10 GHz InGaAs PIN photodiode with preamp (G9822-12) at 1.55um and 2.5 GHz GaAs PIN photodiode array (G8921-01) at 0.85 um are available in open market. Analogue and digital signals can modulate diode lasers by electrical injection at several Gbps rate.

3. Optical Telecom Bottlenecks

Nippon Telegraph and Telephone (NTT) Japan has recently demonstrated capacity of optical transmission at 14 Tbps [8] over a single 160 km long optical fibre. This optical fibre communication capacity (111 Gbps x 140 ch = 14 Tbps) greatly exceeds the current record of about 10 Tbps claiming the world's largest transmission capacity. However, NEC Japan using DWDM capacity of optical fibre has successfully transmitted about 10.9 Tbitps (40 Gbps x 273 ch) over 117km long optical fibre. Vareille and Jullien (France) have demonstrated 3.65 Tbps transmission capacity (11.6 Gbps x 365 ch) over 6850 km long optical fibre. Optical Moor's Law (capacity doubles every four year) has failed to predict correctly after 30 years as today the actual capacity is found to increase ten times in last four years. It is five times more than Moore' Law. By year 2025 fiber capacity of 100 Tbps over 10,000 km or 10 Pbps over 100 km distance is predicted [14]. Possible future data rates are shown in Fig. 5.

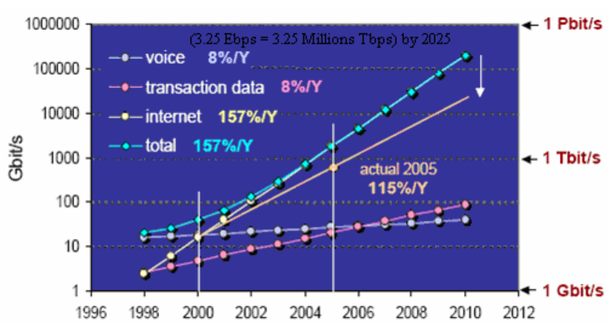

Fig.5 Future (2007 to 2012) communication data rates (Courtesy of Alcatel (Ref.14))

Optical fibre has a tremendous low-loss bandwidth (>25 THz). It is almost impossible to use this bandwidth by transmitting data over a single high data rate channel due to electronics bottlenecks. The optical bottlenecks may include nonlinear effects, (Stimulated Raman Scattering) SRS and (Erbium Doped Fibre Amplifier) EDFA noise [10].

3.1 BW x Length Limitation

Optical pulse broadens after travelling through the optical fibre. Widening of optical pulses due to dispersion is dependent on the square of the data rate. One solution to the dispersion problem could be the transmission of soliton at Tbps but electronic TDM may not be able to multiplex data due its speed limitations as discussed above. However, WDM (not many channels) or OTDM or both can be an alternative. In DWDM communication systems, reduction in dispersion allows phase matching that causes generation of new waves at frequencies that are sums and differences of the mixing waves. Three waves at frequencies f_i, f_j, f_k mix to produce a fourth wave at a frequency f_{ijk}. Dispersion solution over a larger bandwidth (100–350 nm) is also difficult yet be solved along with many others [10, 14]

3.2 SRS Limitations

Scattered photons can travel in forward or backward direction, the bandwidth of the effect is very large (15 THz) and its strength is proportional to the product of pump and Stokes waves. As, the bandwidth of SRS is large; it affects DWDM communication systems and limits the launch power to a less than a mW level for large number of channels. Any increase in the launch power of the pump channel will only worsen the problem. SRS would favour reduction in channel spacing that is contrary to the FWM requirements [10, 15].

3.3 EDFA Noise Limitations

Bandwidth of an EDFA is about 80 nm that can amplify 650 optical channels with a channel spacing of 15 GHz. However, EDFA introduces amplified stimulated emission (ASE) and so the use of optical amplifiers decreases overall signal to noise ratio (SNR) [10, 14-15]. Several techniques have been reported on flat gain amplifiers [16] but still the problem needs attention.

4. Conclusions

Electronics and optical communication bottlenecks invite us to explore new materials, principles and methods to develop (rather invent) high switching speed photonic processors to cope with upcoming Ebps data rates in near future. This increase in speed is not only for optional defence usage but for handling increasing data flow rates. Today global digital data storage is already of order of several Exabytes, which at 40 Gbps rate can hardly be transmitted in 800 years across the globe using present age networks. One year live data of GPS and GIS monitors takes even more time to just browse it. Electronics and telecom bottlenecks are an open challenge to the 21st century telecommunication, electronics and material science engineers and physicists to invent new materials and develop photonic chip manufacturing methods.

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