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Dense Wavelength Division Multiplexing (DWDM) and the Dickson Grating

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1. Introduction

The origin of optical networks is linked to Wavelength Division Multiplexing (WDM) which arose to provide additional capacity on existing fibers. The advent of Dense Wavelength Division Multiplexing (DWDM) has fundamentally changed the economics of core optical networks. Consequently, virtually all operators of long distance fiber optic networks have implemented or are expected to implement DWDM.

DWDM employs different light wavelengths to transmit data parallel-by-bit or serial-by-character. It is a very crucial component of optical networks that will allow the transmission of data, voice, video-IP, ATM and SONET/SDH respectively, over the optical layer.

In today's high-end DWDM systems optimized for core networking, each wavelength (or channel) can operate at up to10 Gbps. Currently available systems support up to about 100 wavelengths per fiber, enabling a single fiber to carry several hundred gigabits of information. Systems supporting terabits per fiber have been demonstrated in laboratories and have been promised for commercial deployment.

Dec 2000 News:
* Claiming a world-best speed record for optical data transmission, researchers at Siemens have transmitted 7 Tbits/s over a single optical fiber using DWDM. That's the equivalent of over 100 million telephone calls or a billion pages of typed data per second. The demonstration was conducted by Siemens' Information and Communication Networks Group at the company's Advanced Optical Networks Laboratories. The researchers simultaneously transmitted 176 channels of 40-Gbit/s data over a 50-km fiber optic cable. The 40-Gbit/s channels, in turn, were produced by time-division multiplexing (TDM) using a prototype of TransXpress FOX, a multiplexer and regenerator system developed by Siemens.

2. Basic DWDM

The term "dense" WDM or DWDM, was once used to signify the use of more than eight wavelengths per fiber. The term DWDM is still generally used to reference high channel count systems. Long-haul DWDM systems take standard optical signals from "clients" such as SONET/SDH network elements, IP routers, or ATM switches, and convert each signal to a distinct, precise wavelength in the 1530- to 1610 nm range. These individual wavelengths are then combined (optically multiplexed) onto a single fiber. In the receive direction of the system, the reverse process takes place. Individual wavelengths are filtered from the multiplexed fiber and converted back to a standard SONET/SDH optical signal to the client. The complete DWDM system typically includes modules for each client interface in addition to equipment for multistage optical combining or splitting of wavelengths, amplification, and management/control, comprising several racks of equipment.

DWDM systems greatly simplify the expansion of network capacity. The only requirement is to install additional interfaces in the DWDM systems at either end of the fiber. The existing optical amplifiers amplify the new channel without the need for additional regenerators. The resultant cost savings will generally more than offset the cost of DWDM systems themselves. For this reason, virtually all core network operators are now deploying DWDM technology. Even new operators with a large number of fibers available will generally use DWDM to increase their capacity before lighting additional fibers.

The most important components of any DWDM system are transmitters, receivers, Erbium-doped fiber amplifiers, DWDM multiplexors and DWDM demultiplexors (mux/demux). Fig 1 shows the structure of a typical DWDM system.

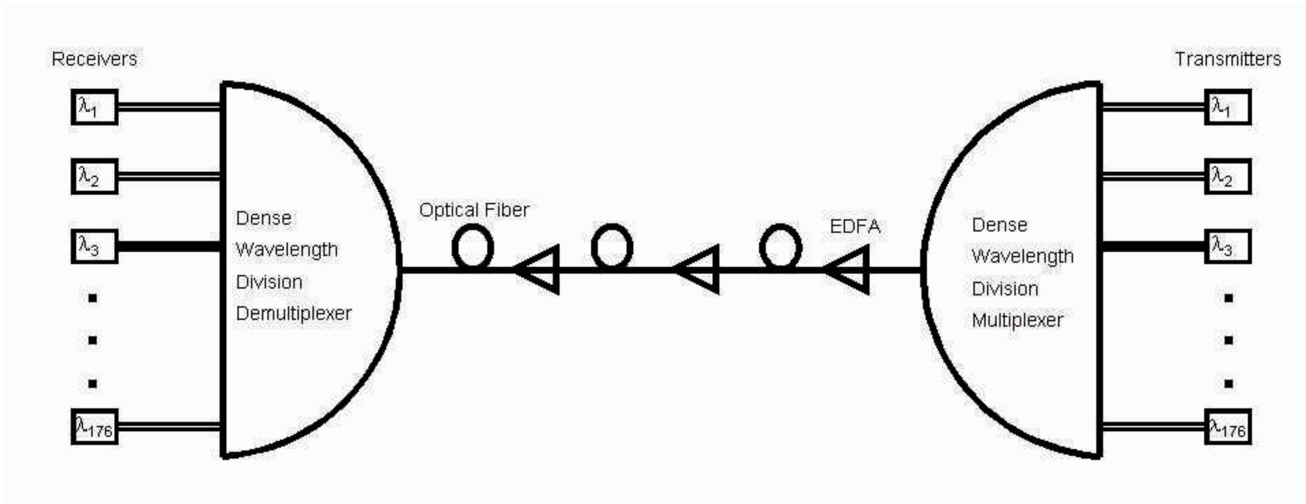

Fig.1 Block Diagram of a basic or typical DWDM System

2.1 Channel Spacing

The minimum frequency separation between two different multiplexed signals is known as the Channel Spacing. Since the wavelength of operation is inversely proportional to the frequency, a corresponding difference is introduced in the wavelength of each signal. The factors controlling channel spacing are the optical amplifier's bandwidth and the capability of the receiver in identifying two close wavelengths. These two parameters set the lower bound on the channel spacing, which ultimately restricts the number of unique wavelengths passing through the amplifier. Taking into consideration the above two factors, the international bodies have established a spacing of 50Ghz (.4 nm) to be the worldwide standard for DWDM. This effectively limits channel bandwidth to something under 40 Ghz

The multiplexer/demultiplexer then has to be able to easily resolve less than .4 nm and should be able to launch at least a hundred wavelengths into as many fibers with minimal losses. Fiber gratings have been useful in providing lower numbers of channels but will not work with tolerable losses as the number of channels rises. Bulk gratings would be a better choice for high resolution but when used at highly dispersive angles they typically fail to diffract both the S and P polarizations at the same efficiency or they do it only at a fairly low efficiency. There are a few special cases where this is not the case and one of them is the Dickson grating design, which has both high dispersion and high efficiency in both S and P polarizations. The efficiency is typically 95% for both all the way through C band and into L band.

The Dickson grating is a volume phase transmission grating, meaning that the light is diffracted as it passes through the grating and there are no absorbing features in the grating itself, only phase modifying transparent structures.

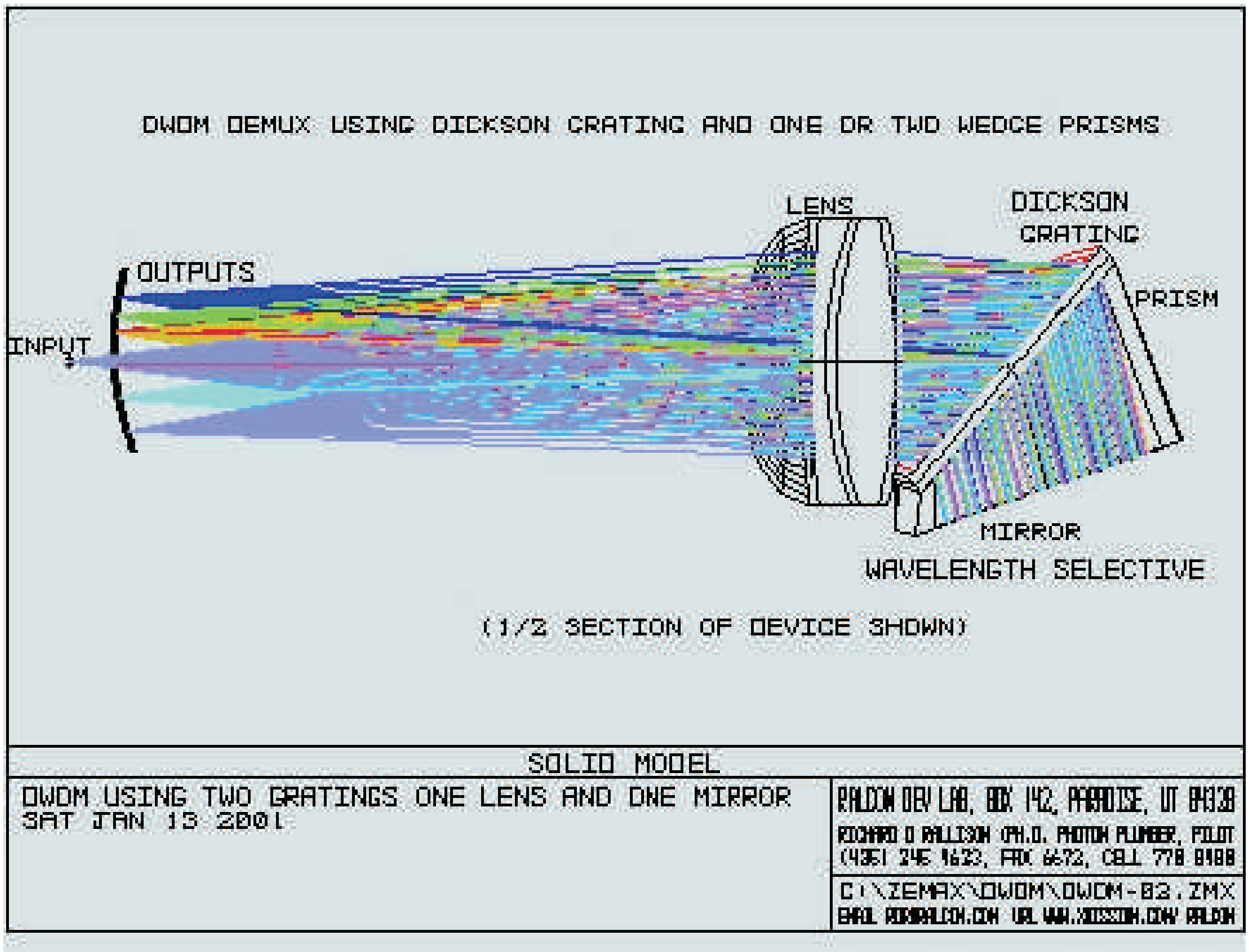

Figure 2. A DWDM configuration using a Dickson grating at 48 degrees

Very high efficiency gratings such as the Dickson grating conserve photons, reducing the required power load in the fibers, reducing nonlinear effects and the number of required EDFAs in a system and therby reducing the cost and required maintenance of the system. The design shown here is only 4 inches long and can resolve 160 channels between 1528 and 1560 nm (C band). Scaling to twice the size will double the number of resolvable channels, but thermal stability and the cost of optics go up disproportionately as does crosstalk.

Ultimately crosstalk limits the minimum space between channels because modulation of the optical carier spreads the spectrum and closer channel spacing just trades off for lower modulation rates. Claims of 100 Gbit modulation with channel spacings of 10 Ghz are ludicrous and while they are being made they should be ignored, bandwidth is never free.

A plot of the diffraction efficiency of a correctly made Dickson grating as a function of wavelength is shown in fig 3. The rolloff in efficiency from 1550 to 1560 or 1528 is barely measureable for either polarization. The efficiency is essentially flat over the whole EDFA bandwidth, inluding the newer extended 1625 to 1620 nm (L band) region. We know of no other grating that can perform at this high level of functionality and can also be easily AR coated on both sides. The Dickson grating is always laminated between two glass substrates and is rugged enough to withstand all normal operating environments, including solvents and temperatures up to 175 C, for years on end. It can also be made in large sheets and is easily replicated by simple optical reproduction in a contact copy configuration.

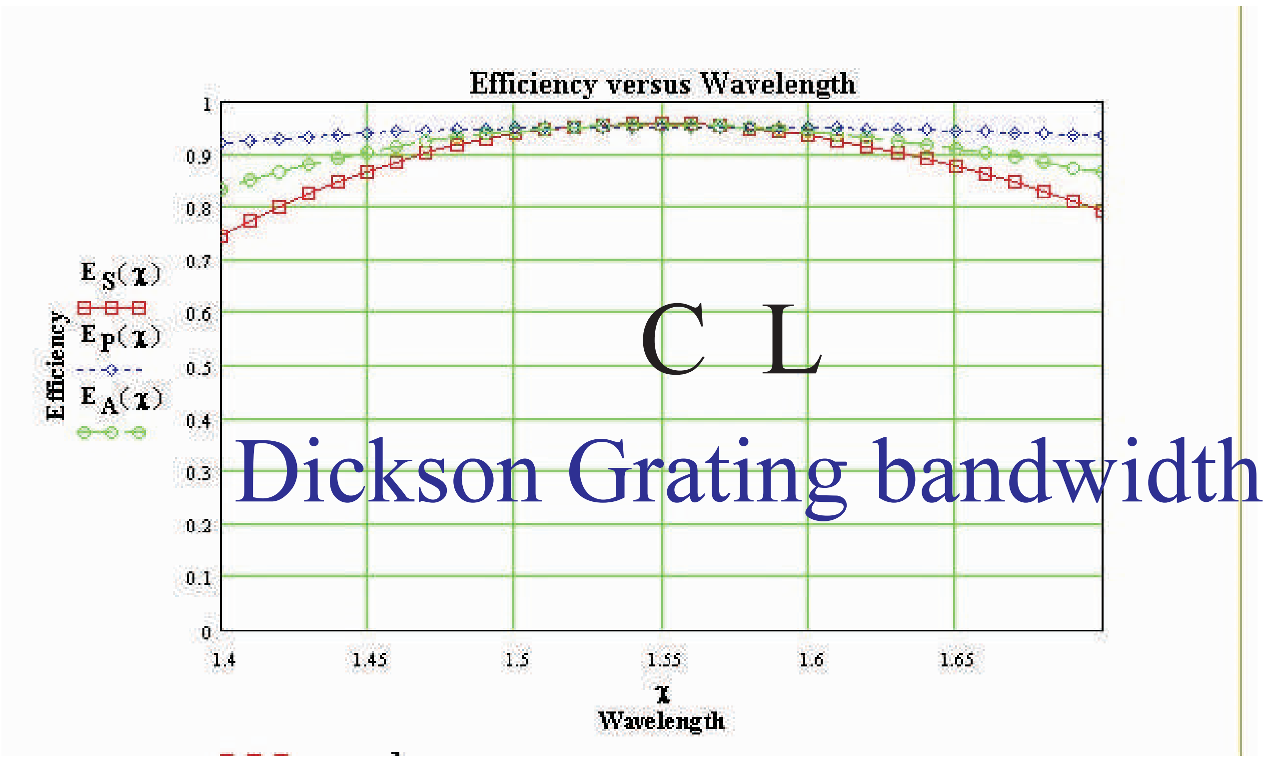

Figure 3. Efficiency plot of Dickson grating designed for 1550 nm

This new grating has the potential for significantly reducing the cost of performing mux/demux operations by significantly reducing the percentage of lost signal in those operations. The improvement is not quite an order of magnitude but thelow .2 db loss aleviates many power related problems with fibers and other devices in the system. It is uniquely polarization insensitive which also greatly reduces the need to amplify and attenuate signals differentially to balance them before multiplexing and launching on a long haul fiber. The savings are out of proportion to the costs because this grating also costs less to make, in small or large numbers, than any other grating in its operating class. Prototypes are available for evaluation at this time and orders can be filled for hundreds or thousands of gratings in a matter of 6 to 8 weeks. Pricing varies with substrate material, size and wavefront specification. Our opinion is that no other grating can compete with the Dickson grating for mux/demux and OSA devices. It disperses at a min of 1.4 mrad/nm, a number that is 2 or 3 times higher than typical and has the absolutely lowest insertion loss of any dispersing component.

3. Other DWDM System Components

Important components of a DWDM system are the Add/Drop Multiplexor (ADM) and the Optical CrossConnect (OXC). The Add/Drop Multiplexor, selectively adds/drops wavelengths without having to use any SONET/SDH terminal equipment. We require the ADM to add new wavelengths to the network or to drop some wavelengths at their terminating points. There are two types of implementations of the ADM, the Fixed WADM and the Reconfigurable ADM. When a system is configured with simple mux/demux devices such as the design in figure 2, which could use the Dickson grating, it is said to be a fixed system or WADM. We would have to add some switching capability to it to make it reconfigurable. Thus far we have no appropriate method for accomplishing fast efficient switching inside the mux/demux unit so it must remain an external function, which it usually is.

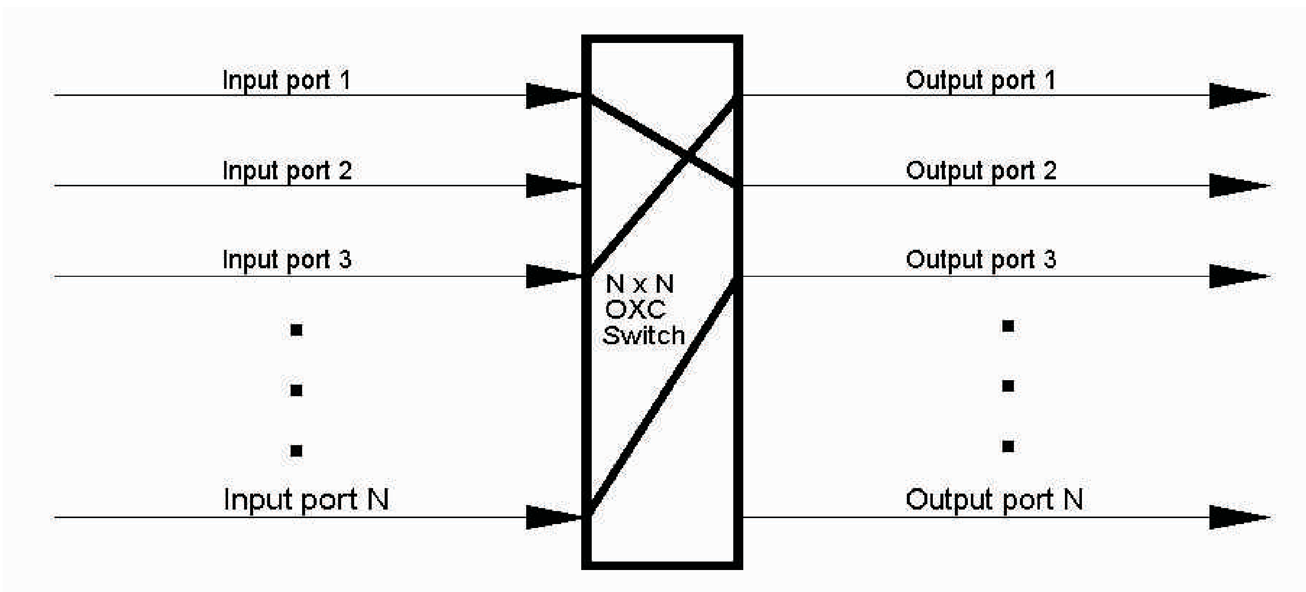

Fig.4 Block Diagram of the OXC, which may be a MEMS device or waveguides etc.

The Optical Cross Connect acts a cross-connect between n-input ports and n-output ports. It allows the efficient network management of wavelengths at the optical layer. The variety of functions that it provides are signal monitoring, restoration, provisioning and grooming.

An optical network consists of wavelength routers and end nodes that are connected by links in pairs. The wavelength-routing switches or routing nodes are interconnected by optical fibers. Although each link can support many signals, it is necessary that the signals be of distinct wavelengths.

Routers transmit signals on the same wavelength on which they are received. An All-Optical wavelength–routed network is that wavelength-routed network that carries data across from one access station to another without any O/E (Optical/Electronic) conversions.

3.1 Categories of Wavelength Switches (routers):

Non-reconfigurable switch: These types of switches, for each input port and each wavelength, transmit onto a fixed set of output ports at the same wavelength. These cannot be changed once the switch is built. Networks that contain only such switches are called non-reconfigurable networks. These are appropriate for our grating modules or mux /demux devices as they are.

Wavelength-Independent Reconfigurable switch: These types of switches have input-output patterns that can be dynamically reconfigured. The input-output pattern is independent of the wavelength

Wavelength-Selective Reconfigurable Switch: These types of switches combine the features of the first two categories. Also known as generalized switches, they basically have both the properties of dynamic reconfiguration and the routing pattern being a function of the wavelength of the incoming signal. This is the device that will mux/demux and switch lanes all in one, and is the toughest to realize.

DWDM by itself provides a "dumb" fiber multiplier, ideally it should have additional optical switching capability to implement dynamically reconfigurable interconnections necessary for the next generation systems. Long haul fiber is requiring less and less frequent regeneration - new ultra-long-haul systems from Nortel, for instance, transmit coherently for up to 2500 miles without regeneration. The aim is to avoid changing data streams that are encoded in light out of light in order to switch them, but the actual process of deciding which switch settings to apply and then actually applying them remains a process for electrons. Optical switching is still a ways off, being only just a laboratory trick at the present.

3.2 Switching technology

Common approaches to waveguide switching include several variations of thermo-optic and electro-optic techniques. Thermo optic switches exploit materials that have slightly different refractive properties at different temperatures. Electro-optical switching approaches use liquid crystals which affect the polarity or phase of the light and make the light tend toward one output waveguide or the other. Another use of liquid crystals is in the switching on and off of gratings and holographic optics that can focus light into a second fiber or let it pass unchanged.

The most widely advertised waveguide approach relies on bubbles. Agilent (Palo Alto, CA - 800-452-4844) - is developing a process that actually draws on HP's ink-jet technologies. In ink-jet technology, heat is used to create bubbles in the ink which are transferred to the page. The bubbles are created inside waveguides, right at the point where the waveguide splits. The liquid converts to a gas where the heat is applied, forms a bubble, and the light passing through the bubble goes in a different direction than the light that passed through before the bubble was formed.

All switching technologies have to be used with grating mux/demux devices and so all can become better performers with the Dickson grating employed as the primary dispersing element. It can be designed into virtually any switching scheme and will always result in improved performance. The current switchable hoe or grating technologies cannot use the Dickson design because it requires a much larger index modulation than is available in switchable materials. The DCG used to make Dickson gratings may be made to be switchable while retaining most of its intrinsic high modulation and if so then that is the direction to pursue in any new research effort. Any material that can be diffused into the grating structure without softening the gelatin is allowed and some of the candidates will also be electro-optically active so that switching would be possible and practical.

4. Summary of developments

With the development of erbium-doped fiber amplifiers, most systems that use IP over DWDM using SONET frames have removed the SONET multiplexors. GTS Carrier Service in March, launched the first high capacity transport platform in Europe that uses IP over DWDM technology. Further more, major carriers such as AT&T, Sprint, Enron, Frontier, Canarie, have all begun to realize the huge economic potential of IP over DWDM and there is no longer any skepticism about this technology.

With carriers adding DWDM capabilities to their fiber networks to handle higher volumes of data traffic, SONET technology is fast becoming obsolete. For example, Williams is already rolling out ATM over fiber with its FLEX-UNISM technology. By using non-zero Dispersion Shifted fiber it has OC-192 capacity. Imagine being able to download the whole of the "Titanic" movie in less than a second. Using DWDM it is now possible to provide OC-48 channels connected directly to ATM and IP network equipment without the extra cost of SONET multiplexors. With the advent of DWDM from R&D labs, providers will now not need to have the expense of laying new fiber to handle bigger loads. Companies like WorldCom and its subsidiary Uunet Technologies already have WDM in their networks to multiply capacity. Providers like Qwest Comm., IXC Communications and Level 3 Communications have started using advanced DWDM systems in their fiber laying stage itself.

A lot of companies now have products ranging from fibers to amplifiers to intelligent Optical switches, routers e.g. Lucent (WaveStar, LazrSPEED fiber, OptiStar), Ciena (MultiWave Core Director), Monterey Networks(bought by Cisco), Alcatel, Nortel Networks, Sycamore Networks, Adva Optical Networking , Williams Network(FLEX-UNISM) etc

It is very possible that a day will come when only two optical layers will exist: WDM layer and IP layer. However, SONET equipment has two features: restoration and trouble-shooting capabilities. For this reason, and also for the reason that a lot of investment into SONET has already taken place, SONET will survive. As routers become faster, it will be difficult to convert every wavelength to add or drop off bandwidth. Thus, managing 100+ wavelength systems is probably the next big challenge. Companies like Alcatel have developed OADMs. Standard bodies like ITU-T, ANSI have declared that optical standards will come into the picture only after 2000. Research work is also being done to try and achieve the difficult goal of a high-speed all-optical network. New concepts such as All-optical switching are coming up. 1 Tbps systems are expected in the market by early 2002/2003. Network providers will start leasing out wavelengths (or "lambdas") instead of leasing lines. Cost will be an important issue in widespread deployment of optical systems. A lot of implementation issues and the development of standards need to be addressed for an all-optical network to come out at a reasonable cost. How soon, or for that matter whether, we will ever achieve an all-optical network is an open question at this time.

In any scenario, the Dickson Grating will improve the performance and lower the initial and operating costs of every likely implementation of DWDM networks and should be deployed as often as it can be.

5. References

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2. Cisco Systems web page http://www.ieng.com/warp/public/cc/so/neso/olso/olne/coint_wp.htm

3.Lee Dickson "Lee Dickson" <leedickson@infowest.com>

6.Acronyms

ADM -Add/Drop Multiplexor
ANSI -American National Standards Institute
AON -All-Optical Network
ATM -Asynchronous Transfer Mode
DBFA -Erbium Fiber-based Dual-band Fiber Amplifier
DWDM -Dense Wavelength Division Multiplexing
EBFA -Extended Band Fiber Amplifier
EDFA -Erbium-Doped Fiber Amplifier
ERION -Ericsson Intelligent Optical Network
IP -Internet Protocol
ITU -International Telecommunications Union
MMR -Modified MultiMeta Ring
MPLS -Multiprotocol Label Switching
MWRS -Multicast-capable Wavelength-Routing Switch
OA -Optical Amplifier
OADM -Optical Add/Drop Multiplexor
OASn -Optical Amplifier Section layer
OCh -Optical Channel layer
O-E-O -Optical to Electronic to Optical
OMSn -Optical Multiplex Section layer
OXC -Optical CrossConnects
QKD -Quantum Key Distribution
UWOA -Ultra-Wideband Optical Amplifier
RWA -Routing and Wavelength Assignment
SDH -Synchronous Digital Hierarchy
SONET -Synchronous Optical Network
SR3 -Synchronous Round Robin with Reservation
SRR -Synchronous Round Robin
TDM -Time Division Multiplexing
WAM -Wide Area Metro
WDM -Wavelength Division Multiplexing