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RADC-TR-81-47
In-House Report
March 1981

WAVELENGTH DIVISION MULTIPLEXING: OVERVIEW OF THE STATE OF THE ART

Eric Rickard

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: RADC-TR-81-47	2. GOVT ACCESSION NO.: AD-A097587	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): WAVELENGTH DIVISION MULTIPLEXING: OVERVIEW OF THE STATE OF THE ART		5. TYPE OF REPORT & PERIOD COVERED: In-House Report
		6. PERFORMING ORG. REPORT NUMBER: N/A
7. AUTHOR(s): Eric Rickard		8. CONTRACT OR GRANT NUMBER(s): N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Rome Air Development Center (DCCT) Griffiss AFB NY 13441		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62702F 45192150
11. CONTROLLING OFFICE NAME AND ADDRESS: Rome Air Development Center (DCCT) Griffiss AFB NY 13441		12. REPORT DATE: March 1981
		13. NUMBER OF PAGES: 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Multiplexing
Wavelength Multiplexing
Chromatic Multiplexing
Optical Multiplexing
WDM
CDM

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report provides an evaluation of the different design techniques for Wavelength Division Multiplexing. Heavy emphasis is placed upon the physical techniques for performing optical demultiplexing. The report includes illustrations and data on different design components along with the pros and cons of each. Also included are future considerations for the design and implementation of Wavelength Division Multiplexing techniques in the fiber optic industry.

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PREFACE

This report is a review of the state-of-the-art in wavelength division multiplexing systems design. A preliminary review of optical components performance as they apply to this multiplexing scheme is done, followed by the actual performance results of prior, tested systems.

The intention of this report is to make available to fiber optic design engineers a reference, which will help them evaluate wavelength division multiplexing technology within the realm of optical communications. The report is designed to be a time saving device with fully documented references to help the designer investigate further the performance of this multiplexing method.

Section 2 reviews the component performances, limitations and considers the future success of each component as it applys to wavelength division multiplexing. Several designs are displayed for each multiplexing method, including hybrid designs. They are included to accentuate the design flexibilities available to the design engineer.

Section 3 is a factual listing of previous research in the wavelength division multiplexing area. This represents a comprehensive listing of nearly all research to date. This section should be a finger tip index to a tremendous source of information on wavelength dependent multiplexing.

For the designer who is considering wavelength division multiplexing this report will serve as a valuable time saver.

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INTRODUCTION

With the current demands on present day communication systems, fiber optics is likely to make a significant impact in the near future. One of the primary reasons for its success will be its ability to handle several multiplexed channels on a single fiber. The ability to multiplex more than 10 signals over a single optic fiber is technilogically feasible today.[1] The particular methods of multiplexing currently in use or under research are space division, time division, and wavelength division multiplexing. Space division uses one fiber per signal making it necessary to use one source and detector for each signal. Even though each signal is sent over individual fibers crosstalk does exist within a fiber bundle using space division. Furthermore, space division is the most elemental method of multiplexing used with fiber and would quickly become uncompetitive with either time division or wavelength division as the channel number grows. This method does not even attempt to utilize the bandwidth capability of the fiber, while time division does send several signals over a common fiber. This is done by sampling each signal at a precise rate so that a synchronous electro-optic coupler can send each signal to a common fiber. The necessity of a synchronous coupler may be prohibitively priced for a particular application; because of the extremely tight tolerances and the large number of active components, the reliability becomes an important design consideration. Recent reports indicate that ten to twelve channels could be multiplexed using this method, with allowable error rates[2]. Lastly, wavelength division best utilizes the bandwidth ability of fiber by sending each signal via its own wavelength. This, too, makes it necessary to use individual sources and detectors; however, it has been theorized that by using wavelength multiplexing the maximum number of channels would be at least a factor of ten greater than today's accomplishment[3]. For that reason wavelength division multiplexing (WDM) is considered to be a very promising method of multiplexing currently being studied in the field of fiber optics.

The attractiveness of wavelength division multiplexing is:

* Components are few in number, reliable, rugged, compact and theoretically are environmentally stable within moderate limits.
* It utilizes the broad bandwidth capability which is inherent in optical fiber.

To date several methods have been tested and some installations have been made. In those systems the primary components consist of the following:

* Prisms
* Mirrors
* Filters
* Lenses
* Gratings

In theory, it is possible to produce a workable WDM to handle at least 160 channels with a 50 A channel spacing within the 0.8 - 1.6 um wavelength region[3]. The current limitations of this theory are the limited availability of suitable sources and detectors. As the spectral width of the sources decrease and the sensitivity of the detectors becomes more precise, a subsequent decrease in channel spacing and an increase in channel number will result. How sufficiently separated the channels are is evident by the cross talk level, while the degree of multiplexer efficiency is measured by the attenuation caused by the multiplexer/demultiplexer. Therefore, the measure of success is reflected in the crosstalk level and attenuation at the demultiplexer since it is the most critical portion of the multiplexing system. It is important to keep in mind that it is relatively easy to stack several signals of various wavelengths in a fiber via multiplexing. It is, however, a more challenging problem to demultiplex those signals successfully. Therefore, the success of the WDM is measured by the ability of its components to seperate each wavelength despite the modal, linear and angular dispersion of the fiber waveguide. For that reason within this paper the demultiplexer will be of primary interest and will be referred to synonymously as a multiplexer or WDM.

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DESIGNS AND EVALUATIONS

2.1 Prisms

The design considerations of WDM are primarily size, cost, consistently accurate production and wavelength characteristics. For example, prism multiplexers are expensive to produce. This is because the two typical designs using prisms require collimating lenses and prisms which are known to be expensive [1]. This multiplexer is also bulky since extremely small prisms are very difficult to fabricate. Thus a small size requirement would further escalate the cost. As in all WDM designs, the principle feature is to spatially separate the signals. Prisms are very good for this; unfortunately, this capability is directly proportional to the size of the prism and the channel separations[1]. To date, few prism multiplexers have been researched so their performance is not well known, but a typical design can be seen in Fig. 1.

2.2 Double Mirrors

An obvious approach to WDM design is the utilization of a double mirror arrangement [2], as seen in Fig. 2. The mirrors may or may not be used as the wavelength selective device within the multiplexer. A previous design using multilayer optical mirrors has been tried as a wavelength selective, double mirror WDM. The recorded losses were 8.2-16.2 dB per multiplexer/demultiplexer system with cross talk levels of at least -42 dB for the four channel WDM[2]. If they are not wavelength selective the actual channel separation could be done by prism[3] or by graded index rod lenses (GRL)[4]. Previous attempts have resulted in channel losses around 4 dB for the multiplexer/demultiplexer system[4]. A possible design might be something similar to Fig. 3. Looking beyond the performance characteristics, the design is generally bulky, not capable of more than a few channels with large separations and expensive due to the large number of components needed[3]. Therefore this WDM type is not considered useful in all but the least stringent communications systems.

2.3 Filters

Although nearly all WDM systems use filters of some sort as insurance against poor signal to noise ratios, few try to use them as the wavelength selective device. Those that have been tried often used dichroic filters as beam splitters[5], as seen in Fig. 4 and 5. This method adheres two fibers together with a dichroic filter sandwiched between them. The fiber ends are polished at either 45 or 22.5 degrees to their longitudinal axis; by sending two different wavelength signals down the same fiber, one will pass through the filter while the other is reflected into a second fiber which is oriented at the proper angle. This method, like all filter type WDM designs is limited to a small number of channels, since if M number of channels are used, (M-1) filters will be needed to separate all the signals. Because of this, one can see that the size is dependant upon the channel number. A typical design of wavelength selective filter design, using something other than a dichroic filter, can be seen in Fig. 6. Previous attempts at making filter type WDM units used interference filters as the preferred type over all others. This is because multiple reflection filters are very difficult to produce with the large number of layers necessary and transmission filters are very suseptible to wavelength errors[1]. The attractive features of interference filters are ease of production, small size capability and low cost[3]. They are, as stated previously, limited in channel number, although they show less loss per channel than prism designs[3]. Very few research efforts have been made thus far with the wavelength selective filter WDM, but those that have been done show channel losses in the multiplexer/demultiplexer system of 2.4-16.8 dB[3]. The crosstalk levels have been low, mostly as a result of laboratory procedure and should not be over rated. The channel separation for two channels was typically 1200 - 3800 A, which in comparison to the theoretical channel separations of 50 A is analogous to sending two cars down a four lane highway. The reason for such large channel separations is most likely due to the large pass band region of the filters. This pass band problem would seem to discourage use of this WDM type; however, they will most definitely have a place in WDM design as beam splitters and cross talk reduction components.

2.4 Lenses

Lenses have also been used extensively in WDM componentry. Primarily their purpose is to collimate either the inserted multiple wavelength beam or to collimate or focus the separated wavelengths at the demultiplexer, as evidenced in several figures throughout this text. Graded index lenses (GRL) are often used as wavelength selective devices[1,3,4,6,7,8,] and consequently are useful in several hybrid WDM designs (ie. GRL/Filter or GRL/Grating). Various designs can be seen in Fig. 8 and 9. The present performance characteristics of this type have been encouraging and further improvement in GRL production should further enhance their position in WDM technology[6].One of the greatest advantages of GRL multiplexers is their small size. It has been theorized that possible packaging of this type could be 1-2 cm long and 2-4 mm in diameter[9]. In fact, one WDM has been built using the GRL/Grating method which was about the size of a paper clip, attesting to the reality of small packaging with this method[8]. Performance characteristics of the GRL method alone have not been extraordinary. Losses per channel are typically higher than most WDM types, but not so much that it should be interpreted as a condemnation of this method, provided it performs sufficiently within a given communications system. They must be appealing as a marketable WDM, based on performance and cost considerations, as evidenced by a fiber optic component manufacturer who has designed and marketed the only WDM to date, using the GRL/Filter method[9].

2.5 Gratings

Diffraction gratings are also used significantly as a wavelength selective devices in WDM design. Specifically, blazed gratings are the desired grating based on current research[10,11]. Several designs have been tried, a few can be seen in Fig. 10 and 11. There has also been some research in chirped grating[12] and silicon grating[13] WDM designs and the results appear promising. The performance characteristics of specific off the shelf gratings and the silicon gratings have been good, but in the future more specially designed gratings will be required. Costs are still relatively high since each WDM made so far has been custom designed and gratings are usually expensive to produce, given the large number of rulings needed[13]. Preliminary research indicates that the silicon grating may perform well at a reduced cost of production since it can be produced by photoetching making it possible to reduce grating cost and size significantly[13]. The packaging of grating systems have been reasonably small, approximately +7.5 mm long and + 2 mm wide. As with nearly all fiber optic components very little is known about thermal effects on performance, but one added feature of the silicon grating is its anticipated environmental stability in comparison to the commercial gratings[13]. As far as performance of tested designs they have handled successfully 2-5 channels with typical losses of 2.8-10 dB and crosstalk of at least -30 dB.

2.6 Design Considerations

From a component or system designer stand point it is useful to understand that the losses are not related to the number of channels being multiplexed by a prism or diffraction grating[14]. This means that the eventual handling of large channel numbers will most likely rely on one of those two methods. If cost, size, reproducibility and performance are considered, the diffraction gratings appear to have a distinct advantage. However, along with the gratings will come the necessity and complications of laser diode sources[14]. This is made necessary by the narrow spectral width of the laser diode in comparison to the LED sources which have too wide a spectral operating range to perform successfully with either gratings or prisms when large channel numbers are needed. The graded index rod lens should be included in the list of potential high channel number WDM components. As size limitations become more of an issue these elements will help fulfill the requirements as a hybrid multiplexer. Further development is needed, but success appears to be around the corner. If low channel number is a design parameter and WDM is still considered applicable, then intereference filters and LED sources could be the most likely candidate based on cost and performance characteristics[14]. The cutoff wavelengths of the filters can usually be found sufficiently large enough to decrease the crosstalk level. However, the greater the size of the cutoff region the more limited the system will be in channel number.

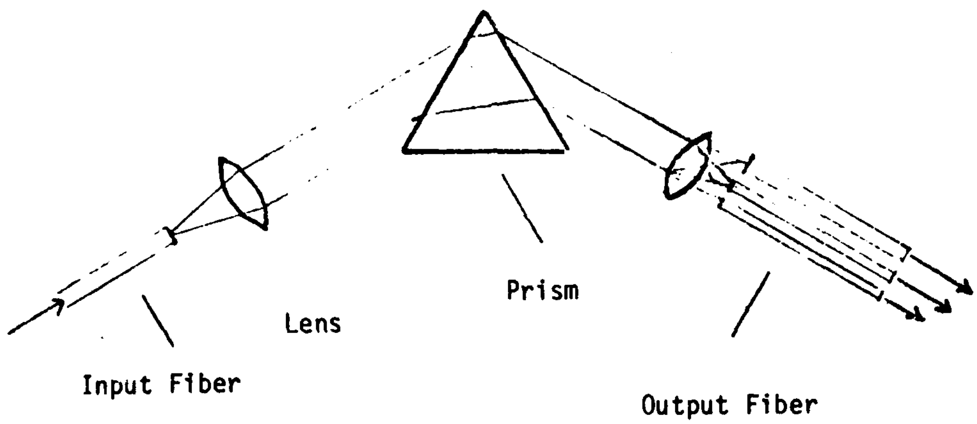

Fig 1

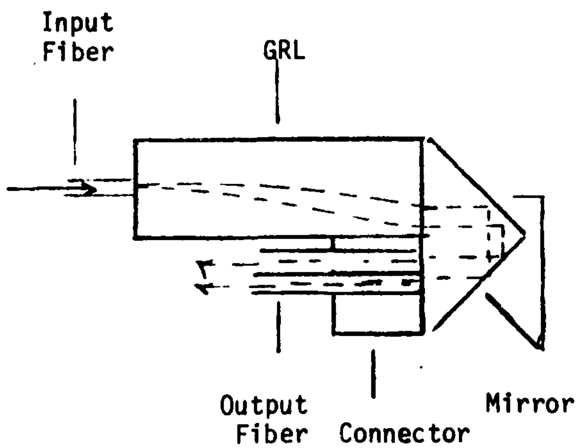

Fig 2

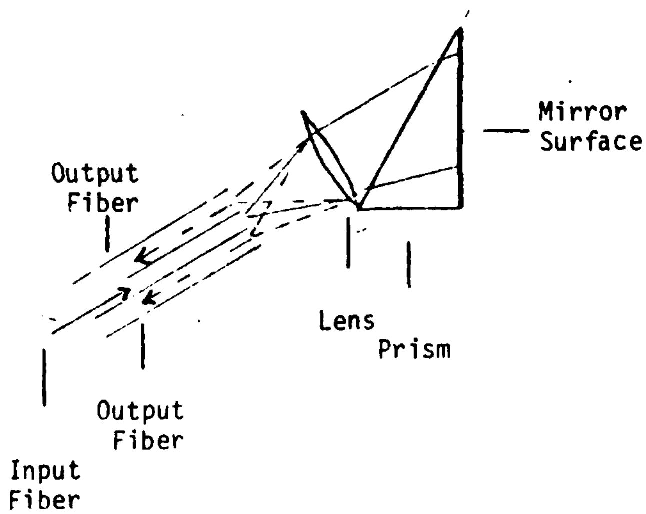

Fig 3

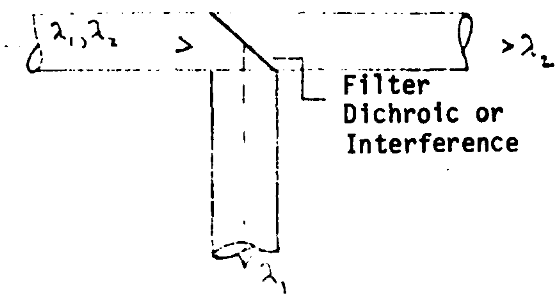

Fig 4

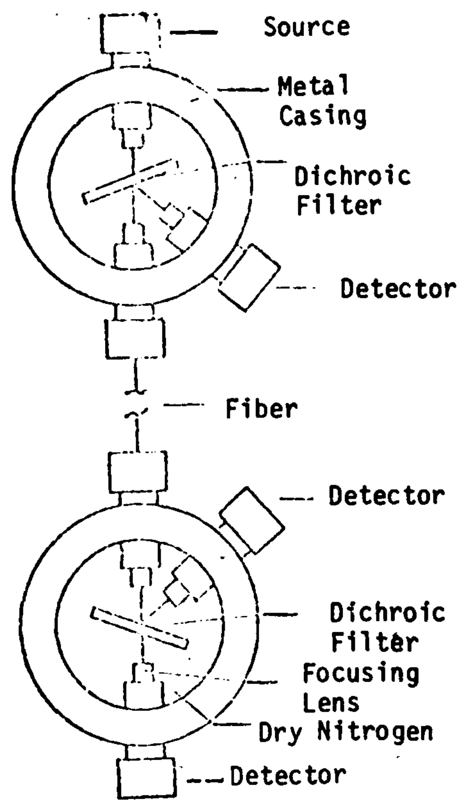

Fig 5

SOURCE: ICE Book #1
Connectors, Splices + Couplers, 1978

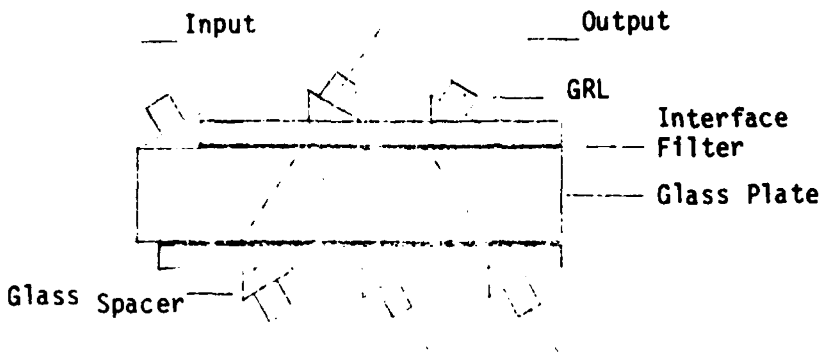

Fig 6

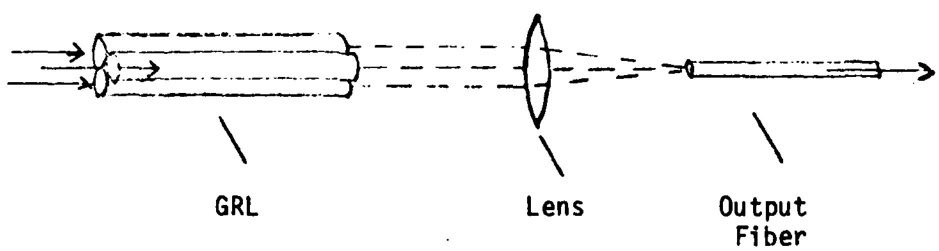

Fig 7

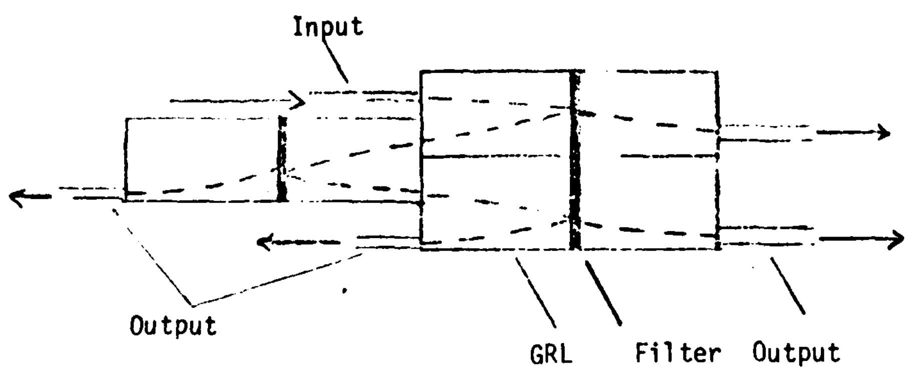

Fig 8

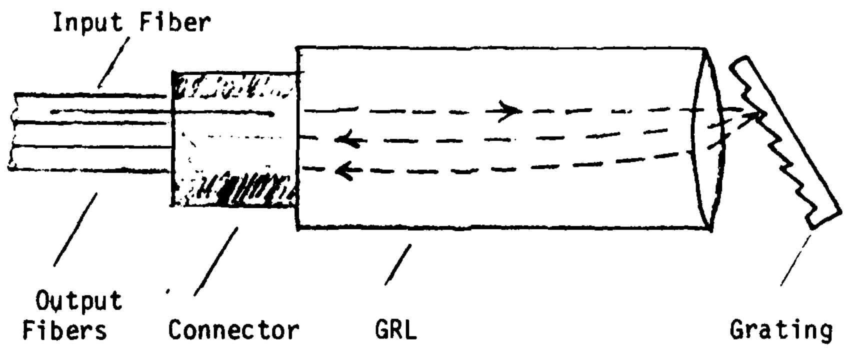

Fig 9

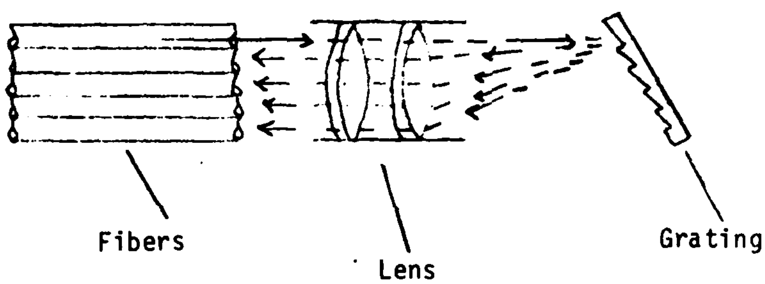

Fig 10

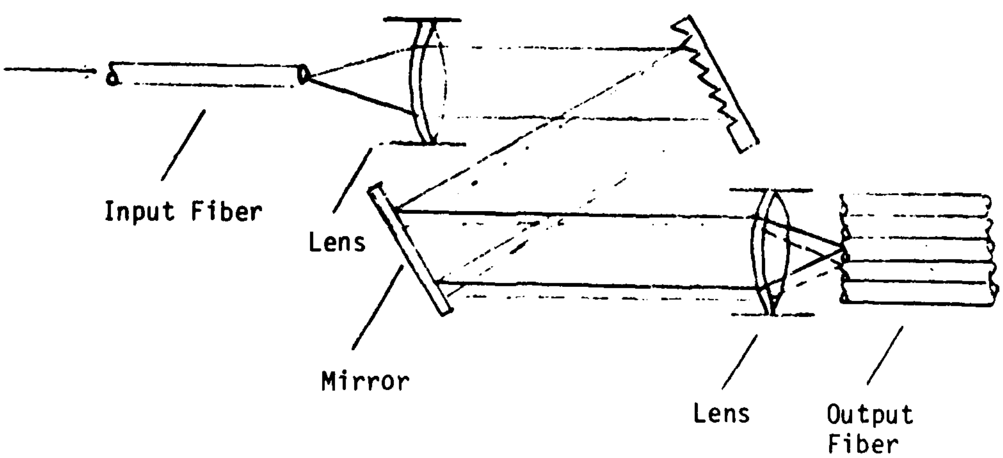

Fig 11

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SECTION 3

STATE OF THE ART WDM INFORMATION AND DATA

3.1 Components: Pros and Cons

The following list is a general overview of components which are used in WDM designs. It is by no means a comprehensive or conclusive listing since certain generalities that are listed can be altered or controlled within limits. This means that the components are not judged to be good or bad, better or worse. It is up to the system engineer to evaluate the performance and economic conditions within which the component must exist as it applies to a particular fiber optic communications system.

PROS AND CONS OF VARIOUS WDM COMPONENTS

PRISMS	High channel number capability	Needs collimated input/output
	Angularly dispersive	Needs laser source for high channel numbers
		Expensive
		Bulky
MIRRORS		High channel losses
		Bulky
		Expensive
		Low channel capacity
FILTERS	Low channel losses	Losses are a function of channel number
	Reduces crosstalk level	Size is a function of channel number
	Can use LED sources	
LENSES	Small size capability	Larger aberrations than theorized
	Moderate channel losses	
	High channel capacity	

GRATINGS	Small size capability	Needs laser sources for large channel numbers
	Low channel losses	Presently uses commercially available products
	Potentially low priced	
	Angularly dispersive	

3.2 Systems

The following information and data have been located in several references and compiled in an easy to use matrix. It is subdivided horizontally among the various multiplexing types. Note that some sources are referenced several times for different multiplexing techniques when these sources described more than one method. Along with the information, some particular references , indicated by capital letters A-O, are made to a point of interest and are listed on page 3-8.The matrix is also divided vertically among reference number, sources and detectors used, input fiber core and diameter, WDM type, wavelengths used and system results.

Unless otherwise noted all losses per channel are assumed to be for the entire WDM system (multiplexer/demultiplexer being the same).The initials listed with the fiber measurements indicate either graded index (GI) or step index (SI) fibers were used. A list of the more common acronyms within the matrix follow:

LED = light emitting diode

LD = laser diode

PIN = pin diode

APD = avalanche photo-diode

GRL = graded rod lens

IF = interference filter

Dbl. = double

S/D = source/detector

X-talk = cross talk

Mux/Demux = multiplexer/demultiplexer

	SYSTEM COMPONENTS				WDM RESULTS		
Ref.	S/D	Fiber Core	Fiber Dia	WDM Type	Operating Wavelength	Mux/Demux Loss/Chan	X-Talk Min.
1	LED/APD	SI 60	150	GRL	.784,.825,.858	12dB A	
				Prism		7 dB B	
2	Laser/	GI 50	125	GRL	.805,.817,.863	2.4-3.0dB C	-24dB
	APD			Prism		2.9-3.3dB D	
3	LED/APD			Dbl.	.84,1.20	4 db	
				Mirror			
4	LED/APD			Dbl.	.75,.82,.90,1.2	8.2- 16.2dB	-35dB
				Mirror			
5	LED/APD			Mirror	.74,.82,.90,1.06	5.7- 8.2dB	-23dB
6	LED/APD	SI100		IF	.75,.83,.90,1.2	8.2- 16.8dB	-47dB
6	LED/APD	SI100		IF	.75,.83,.90,1.06	15.2- 26dB	-47dB
7	LED/APD			Filter	.80,1.2	2.4-3.0dB	-18dB
1	LED/APD	SI 60		IF	.75,.83	8.0-8.4dB	-49dB

SYSTEM COMPONENTS				WDM RESULTS			
Ref.	S/D	Fiber Core	Fiber Dia	WDM Type	Operating Wavelength	Mux/Demux Loss/Chan	X-Talk Min.
8				IF	.725,.765,.81, .85,.89,.92	2.6-4.0dB	
9	LD/			Fil/GRL	.85,.89	10dB	-19dB
"	LED/			"	.78,.88	20dB	-27dB
"	LD/			"	.83,.87,.89	10dB	-19dB
"	LED/			"	.73,.83,.88	20dB	-27dB
"	LD/			"	.83,.85,.87,.89	10dB	-19dB
"	LED/			"	.73,.78,.83,.88	20dB	-27dB
10	LED/APD	GI 55	125	Dichroic Coupler	.82-.86,1.04-1.08	7.6-16.8dB E 6.4-7.8dB F	-40dB -34dB
3				GRL	.80,.87	7.6dB G 11.6dB H	
11 I	LD/APD	SI 60	150	Grating	.81,.83,.85,.87,.89	3.4dB	-30dB
11 J	LD/APD	GI 60	150	Grating	.81,.83,.85,.87,.89	2.8-4.4dB	-30dB
12 K	LD/APD	GI 60	150	Grating	.81,.83,.85,.87,.89	3.4-4.2dB	-30dB
12 L	LD/APD	GI 60	150	Grating	.81,.83,.85,.87,.89	6-10dB	-30dB
13	LD/APD	GI 60	150	Silicon Grating	.80,.825,.85,.875,.90	4.4-5.0dB	-30dB
3 M	LED/APD			Grating	.75,.83,.90,1.20	5-13.2dB	

	SYSTEM COMPONENTS				WDM RESULTS		
Ref.	S/D	Fiber Core	Fiber Dia	WDM Type	Operating Wavelength	Mux/Demux Loss/Chan	X-Talk Min.
3 N	LED/APD			Grating	.75,.83,.90,1.204.	5-16dB	
14	Laser/ PIN	GI 55	110	Grating GRL	.50,.633	5.6dB	-30dB
15	Laser/	GI 55	110	GRL/ Grating	1.104-1.128	5.2 dB	-29dB
16 O	Laser/			Grating Prism	.607,.627		

Note: All wavelengths and fiber measurements are measured in microns (um).

Footnotes:

A. Multiplexer

B. Demultiplexer

C. Multiplexer

D. Demultiplexer

E. This is for the two channel low pass filter system

F. This is for the two channel high pass filter system

G. For .80 um channel

H. For .87 um channel

I. Output fiber is 2m. long,step index,130 um core

J. " " " " " " " 100 um core

K. " " " " " " " 100 um core

L. " " " " " graded index, 100 um core

M. 4 km. length system, LED power output is -17 to -14 dBm.

N. 14.1 km. length system, LED power output is -14 to -21 dBm

O. Chirped grating

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CONCLUSION

It appears that WDM is in a critical stage of development. Preliminary theory and research make the future look bright. With improved sources, detectors, waveguides and WDM components, optical communications systems should be overwhelmingly competitive with metal cable.

Further research is needed in select areas of component design and implementation. Mysteriously several important aspects of WDM design have rarely been mentioned. Nonetheless, areas to be further researched in the WDM componentry area before complete evaluation can be made include:

* Evaluation of environmental effects on componentry performance
* Reduction in component size
* Field installation by moderately trained personnel
* Ways to insure proper axial and angular insertion into WDM so as to further reduce installation problems and enhance performance

Unfortunately it appears that as channel numbers increase so might the packaging. This may be a necessary compromise providing the economics and performance of the system are deemed reasonable. Although it has not been previously mentioned, alignment within the WDM is a critical factor to the performance of all types[7]. It is essential to WDM design to be able to predict the exact location of each signal in the multiplexer. As the the channel numbers increase and the packaging size decrease the necessity to locate the signal will become even more critical.

There exists within the field of fiber optics the feeling, perhaps unfounded, that this technology will go the same way that silicon chip technology went. This hope is based on the rapid improvements in fiber component performance in the last few years. If this is in fact the trend of the future then it seems likely that WDM will improve as the sources, detectors and other system components improve further.

The research which has been done in WDM design is still in its infancy. With that in mind it should be remembered that essentially all the results of prior research have been conducted under controlled conditions and installed by highly skilled technicians with the necessary equipment. Even those systems presently in the field are custom designed and installed. Therefore, the results contained within this report should be assessed as the best available to date, but by no means the limit of the future.

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