POLARIZATION MODE DISPERSION IN OPTICAL COMMUNICATION

A DISSERTATION

SUBMITTED IN PARTIAL
FULFILLMENT OF THE REQUIREMENT FOR THE
AWARD OF THE DEGREE OF

MASTER OF ENGINEERING
IN
ELECTRONICS AND COMMUNICATION

UNDER THE ESTEEMED GUIDANCE OF

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CERTIFICATE

This is to certify that the major thesis dissertation entitled "**POLARIZATION MODE DISPERSION IN OPTICAL COMMUNICATION**" submitted by Poonam Singal Roll No:4602, is being submitted to the university of Delhi towards the partial fulfillment for the degree of Masters of Engineering in Electronics & Communication. To the best of my knowledge the work in this dissertation has not been submitted in part or full for the degree or diploma in any other college or university.

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Poonam Singal

ABSTRACT

Polarization mode dispersion means in the simplest case that an optical fiber exhibits a differential group delay between two orthogonal principal states of polarization. PMD is a big obstacle for high capacity long haul optical communication systems. All telecom carriers with fiber plants dating from 1995 or earlier have problems transmitting 40 Gb/S signals, sometimes even at 10 Gb/s.

A study demonstrating the effect that PMD has on signal propagation in a fiber and on system performance has been made. A 40 Gbps Rz signal is launched into a fiber span of 100 Kms. PMD effect is turned on with different PMD coefficients, the fiber is simulated and effect on the eye diagram & bit error rate is studied.

Practical measurement using WIN –PMD instrument at ORDINANCE CABLE FACTORY have also been done.

Further Photonic crystal fiber have been explored as polarization maintaining fiber as their structure could be modified to increase birefringence. Polarization division multiplexing is an alternate for doubling the spectral efficiency. PMD is the major obstacle faced by that, if somehow the fibers with low PMD or some sort of compensation technique could be devised results are better. High data rate could be achieved. Suitability of Photonic Crystal Fibers for Polarization Division Multiplexing has been shown.

CONTENTS

CHAPTER 1

INTRODUCTION

1a. Polarization

In electrodynamics, polarization is the property of electromagnetic waves, such as light, that describes the direction of their transverse electric field. More generally, the polarization of a transverse wave describes the direction of oscillation in the plane perpendicular to direction of travel .Longitudinal waves such as sound waves do not exhibit polarization because for these waves the direction of oscillation is along the direction of travel. The electric field vector may be arbitrarily divided into two components labeled X and Y. The two components may not have the same amplitude, and may not have the same phase. The shape traced out in a fixed plane by the electric vector as such a plane wave passes over it is a description of the polarization state. (Fig. 1)

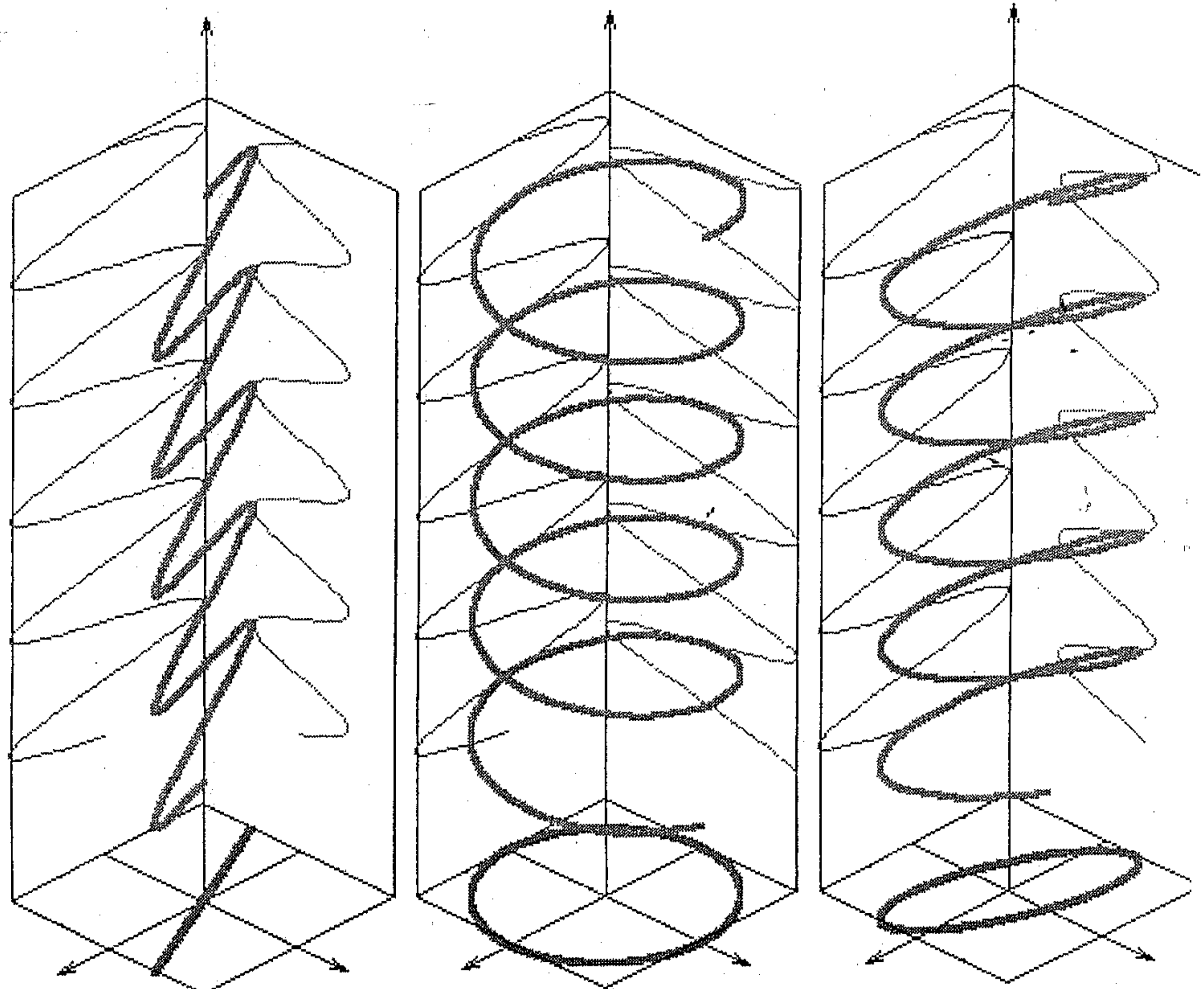
LINEAR POLARIZATION

When the two orthogonal components are in phase, the tip of the vector traces out a single line in the plane, is called Linear Polarization.

CIRCULAR POLARIZATION

When the two orthogonal components are exactly 90 degree out of phase, their amplitudes are equal, the electric vector traces out a circle in the plane, this is called Circular Polarization. Depending on which way the electric vector rotates is called Left Hand or right Hand Circular polarization.

ELLYPTICAL POLARIZATION



Linear *Circular* *Elliptical*

When the two components are not in phase and either do not have the same amplitude and are not 90 degree out of phase, the electric vector traces an ellipse in the plane, called Elliptical Polarization.

1b. Polarization mode dispersion

Even a single mode fiber is not truly single mode because it can support two degenerated modes that are polarized in two orthogonal directions. Under ideal conditions (perfect cylindrical symmetry and stress free fiber) , a mode excited with its polarization in x would not couple to the mode with orthogonal Y – polarization state . In real fibers , small departures from cylindrical symmetry because of random variations in core shape and stress induced anisotropy result in a mixing of the polarization states by breaking the mode propagation constant β becomes slightly different for the modes polarized in X and Y directions . This property is referred to as modal birefringence .

The strength of modal birefringence is defined as

$$B_m = \frac{|\beta_x - \beta_y|}{K_o} = |n_x - n_y|$$

Where n_x and n_y are the modal refractive indices for two orthogonaly polarized states . for a given value of B_m , the two modes exchange their powers in a periodic fashion as they propagate inside the fiber with the period

$$L_B = \frac{2\Pi}{[\beta_x - \beta_y]} = \lambda / B_m$$

The length is called 'Beat Length' . The axis along which the mode index is smaller is called the fast axis because the group velocity is larger for light propagating in that direction . Similarly the axis with the larger mode index is called the slow axis.

In standard optical fibers , B_m is not constant along the fiber but it changes randomly because of fluctuations in the core and anisotropic stress . As a result , light launched into the fiber with a fixed state of polarization changes its polarization in a random fashion . This becomes an issue for optical communication system when short pulses are transmitted over long lengths . If an input pulse excites both polarization components , the two components travel along the fiber at different speeds because of their different group velocities . The pulse becomes broader at the O/P end because group velocities change randomly in response to random changes in fiber birefringence . This phenomena is referred to as **POLARIZATION MODE DISPERSION** and has significant role in long haul light wave systems .

1c. Birefringence

The birefringence is defined by the difference between the propagation constants of the polarization Eigen modes , that is

$$\Delta\beta = \beta_x - \beta_y$$

Birefringence could be intrinsic perturbation birefringence or elliptical core birefringence or internal stress birefringence , extrinsic perturbation or lateral stress .

EXTENT OF PULSE BROADENING IN PMD

Extent of pulse broadening can be estimated from the time delay ΔT occurring between the two polarization components during propagation of an optical pulse . For a fiber of length L constant birefringence B_m , ΔT is given by

$$\Delta T = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right| = L\ |\beta_{1n} - \beta_{1y}| \longrightarrow (1)$$

Where $\delta\,\beta_1 = K_o$ (dBm / dw) is related to fiber birefringence . The equation 1 can not be directly used to estimate PMD for standard telecommunication fibers because of random changes in birefringence occurring along the fiber . These changes tend to equalize the propagation times for the two polarization components . In fact PMD is characterized by root mean square(RMS) value of ΔT obtained after averaging over random perturbations . The variance of ΔT is found to be

$$\partial^2{}_T = [\,(\Delta T)^2\,] = 2\,(\Delta'\,l_c)^2 \exp\left| \frac{-L}{l_c} + \frac{L}{l_c} - 1 \right|$$

Where Δ' is the intrinsic modal dispersion and correlation length l_c is defined as length over which two polarization components remain correlated. Typically l_c is 10m .

$$\partial_T = \Delta'\,2\sqrt{2\ l_c L} = D_p\ \sqrt{L}$$

Generally D is 0.1-1 ps / $\sqrt{Km}$

Because of its $\sqrt{L}$ dependence , PMD induced pulse broadening is relatively small compared with GVD effects . PMD becomes a limiting factor for high speed communication systems designed to operate over long distances near the zero dispersion wavelength of fiber .

1d. Polarization maintaining fibers

For some applications , it is desirable that fibers transmit light without changing its state of polarization. Such fibers are called polarization maintaining or polarization preserving fibers . A large amount of birefringence is introduced intentionally in these fibers through design modifications so that relatively small birefringence fluctuations are masked by it and do not affect the state of polarization significantly .

PMD COMPENSATION

Progress towards 40 Gb/s polarization mode dispersion compensation is presented in several areas . A single wave plate polarization scrambler that generates stoke's parameters with three harmonics has been realized . Together with an arrival time detection scheme , it allows detection of about 1 ps of PMD within 2.4 μs in 40 Gb/s NR Z transmission setup . A scrambler that operates independent of its input polarization has also been realized . both scramblers can be shared among a number of WDM channels for which PMD is to be detected .

CHAPTER 2

CODING IN C++

2a. Program to calculate Bessel Functions Used in calculation of Birefringence

```
#include<iostream.h>
#include<conio.h>
#include<math.h>

fact(int n)
{
        int i,f=1;
        for(i=1;i<=n;i++)
                f=f*i;
                return(f);
}

void main()
{
        clrscr();
        int k,n;
        double sum=0.0,term,p1,p,jn1,jn2,jn,x,f1,f2,f3;
        cin>>x>>n;
        p1=pow(x,2);
        p=-p1/4;
        k=0;
```

```
f1=1;
f2=1;
f3=fact(n);
do
{
        term=f1/(f2*f3);
        sum=sum+term;
        k++;
        f1=f1*p;
        f2=f2*k;
        f3=f3*(n+k);
}
while(fabs(term)>0.000001);
jn1=(double) x/2;
jn2=pow(jn1,n);
jn=(double) jn2*sum;
cout<<jn;getch();
```

2b. Program to calculate Birefringence of Elliptical core

```
#include<iostream.h>
#include<conio.h>
#include<math.h>

float bessel(float x, int n);
fact(int n);

void main()
{
        clrscr();
        float pi=3.1414142;
        float w,u,v,j0,j1,x,y,z,a1,b1,a,b,n1,n2,lm,k0,del,delb,G,E,del2;
        cout<<"ENTER THE WAVEGUIDE PARAMETERS (U,V,W) :";
        cin>>u>>v>>w;
        j0=bessel(u,0);
        j1=bessel(u,1);
        x=pow(w,2);
        y=pow(v,4);
        z=pow(u,2);
        a1=pow((j0/j1),2);
```

```
        b1=pow((j0/j1),3);
        G=(x/y) * (z + ((z-x)*a1) + (u*x*b1));
        cout<<"ENTER THE WAVELENGTH :";
        cin>>lm;
        k0=2*pi/lm;
        cout<<"ENTER THE CORE AND CLADDING REFRACTIVE INDICES (N1,N2) :";
        cin>>n1>>n2;
        del=(n1-n2)/n1;
        cout<<"ENTER THE MINOR AND MAJOR AXIS OF THE ELLIPTICAL CORE (A,B)
:";
        cin>>a>>b;
        E=1-(a/b);
        del2=pow(del,2);
        delb=E*n1*k0*del2*G;
        cout<<"THE BIREFRINGENCE IS: "<<delb;
        getch();
}

float bessel(float x, int n)
{
        int k;
        float sum=0.0,term,p1,p,jn1,jn2,jn,f1,f2,f3;
        p1=pow(x,2);
        p=-p1/4;
        k=0;
        f1=1;
        f2=1;
        f3=fact(n);
        do
        {
                term=f1/(f2*f3);
```

```
            sum=sum+term;
            k++;
            f1=f1*p;
            f2=f2*k;
            f3=f3*(n+k);
        }
        while(fabs(term)>0.000001);
        jn1=(double) x/2;
        jn2=pow(jn1,n);
        jn=(double) jn2*sum;
        return(jn);
}

fact(int n)
{
        int i,f=1;
        for(i=1;i<=n;i++)
            f=f*i;
            return(f);
}
```

RESULT

ENTER THE WAVEGUIDE PARAMETERS (U,V,W) :1.528 2 1.29
ENTER THE WAVELENGTH :1.55
ENTER THE CORE AND CLADDING REFRACTIVE INDICES (N1,N2) :1.46 1.45
ENTER THE MINOR AND MAJOR AXIS OF THE ELLIPTICAL CORE (A,B) :2.5 3
THE BIREFRINGENCE IS: 2.218857e-05

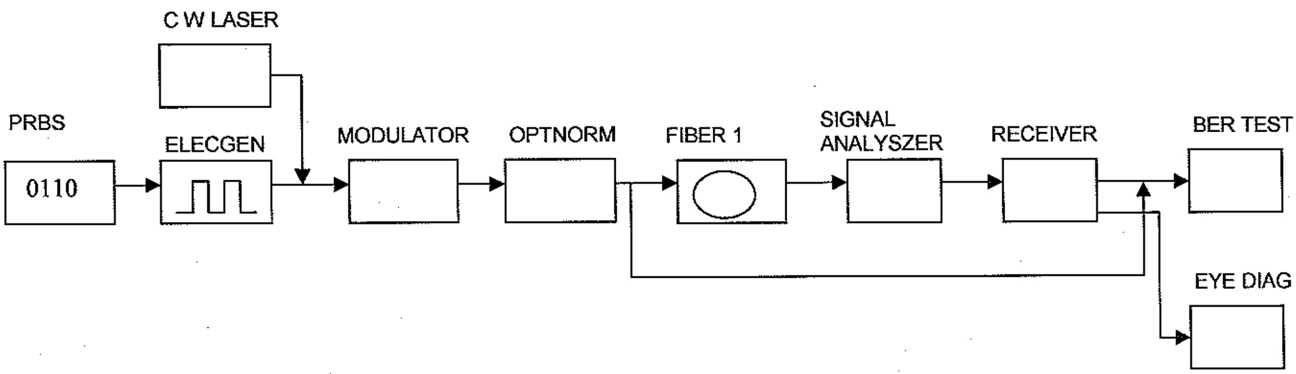
ENTER THE WAVEGUIDE PARAMETERS (U,V,W) :1.528 2 1.29
ENTER THE WAVELENGTH :1.546
ENTER THE CORE AND CLADDING REFRACTIVE INDICES (N1,N2) :1.46 1.45
ENTER THE MINOR AND MAJOR AXIS OF THE ELLIPTICAL CORE (A,B) :1 3
THE BIREFRINGENCE IS: 8.898391e-05

ENTER THE WAVEGUIDE PARAMETERS (U,V,W) :1.7837 4.164 3.7626
ENTER THE WAVELENGTH :1.546
ENTER THE CORE AND CLADDING REFRACTIVE INDICES (N1,N2) :1.48 1.44
ENTER THE MINOR AND MAJOR AXIS OF THE ELLIPTICAL CORE (A,B) :2.5 3
THE BIREFRINGENCE IS: 0.000162

CHAPTER 3

PMD IN OPTICAL COMMUNICATIONS

3a. Effect of PMD on high bit rate
-- A study using Opt – Sim Software



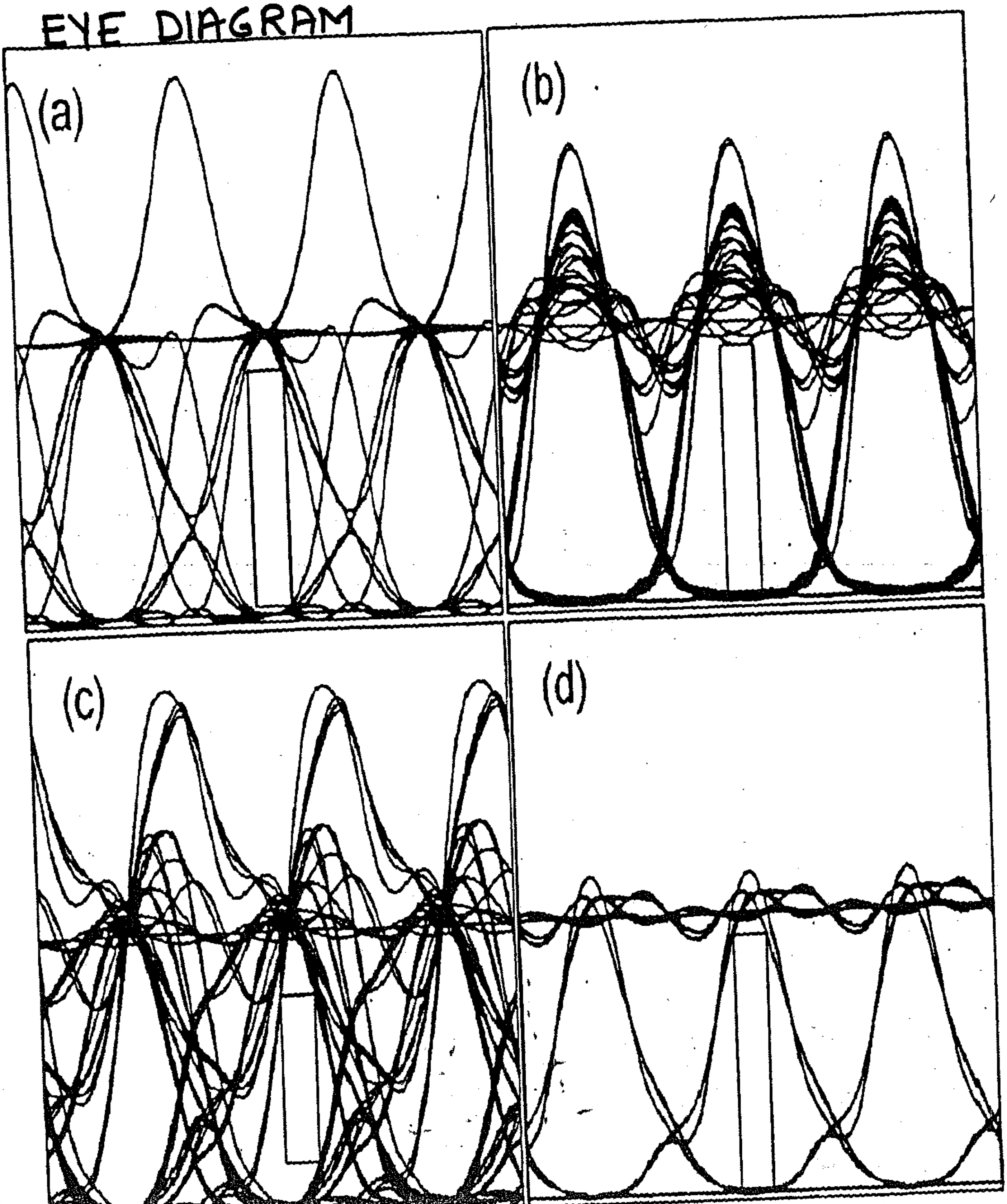
This project demonstrates the effect that PMD has on signal propagation in a fiber and on system performance. For this set up, a transmitter consists of 40 Gbps PRBS generator, CW laser source at 1550 nm., electrical driver, external modulator, optical power normalizer. A 40 Gbps RZ signal is then lunched into a receiver. Length of the fiber span is 100Km. In the fiber model, PMD effect is turned ON. We simulate fiber with two different values for PMD coefficient 0.1 & 1.0 ps / √ KM corresponding to cases for low PMD and high PMD fibers. PMD is statistical effect caused by randomly varying birefringence. Simulations are different for different randomized parameters. PMD causes DGD between X & Y polarization components during propagation in fiber and hence eye distortion at the receiver. Mean DGD can be calculated as

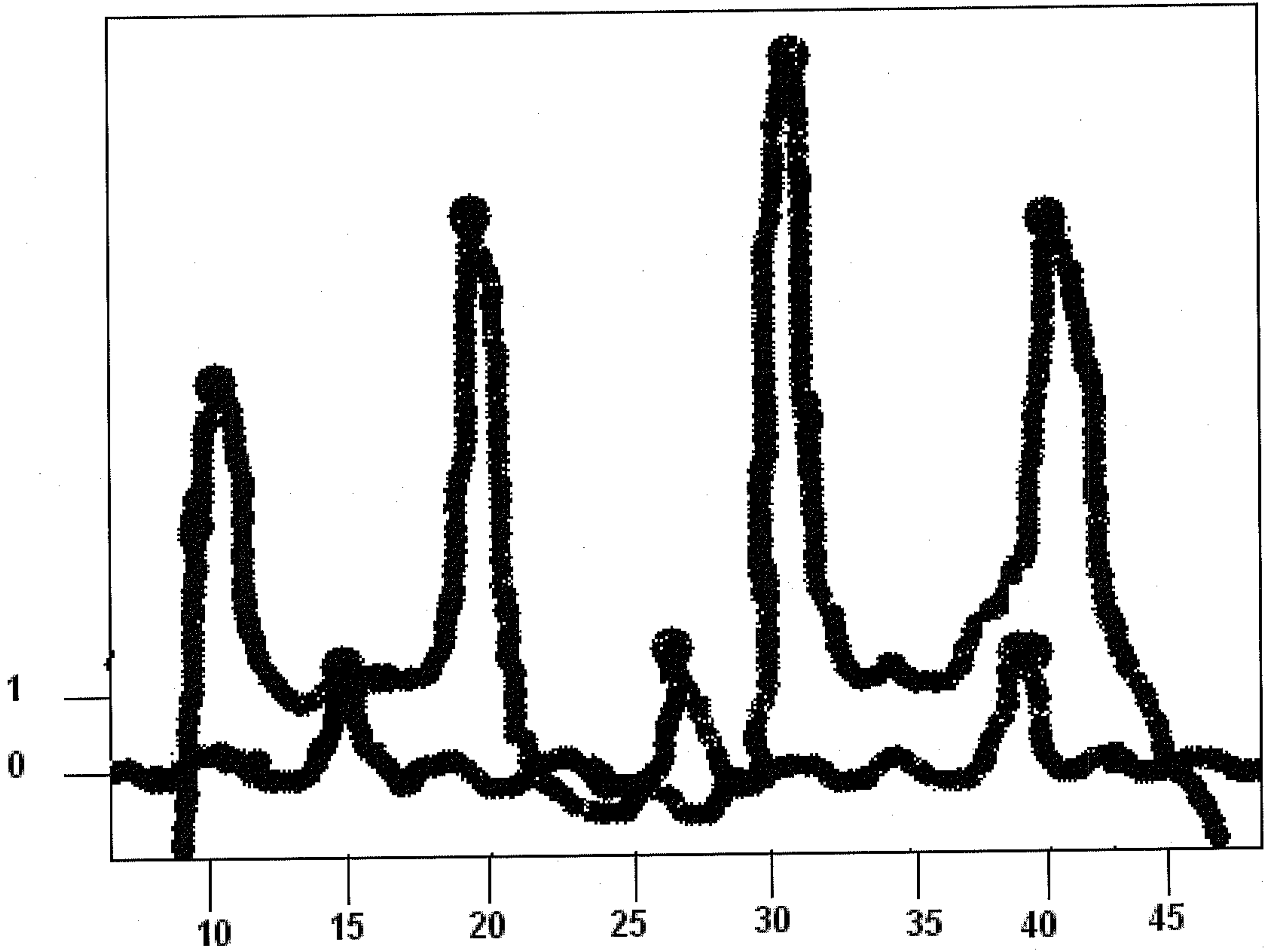
$$DGD_{mean} = PMD_{coff.} \times (L_{fiber})^{1/2}$$

In our case, it will be 1 & 10 ps respectively. For 40 Gbps system, bit duration is 25 ps, thus we export higher PMD penalties for 10 ps and DGD compaed to 1 PS with no PMD effect selection, the system will perform with BER = 10^{-10} and Q = 16 dB.

For a parameter scan of low and high PMD cases, BER, Q factor & eye diagram were observed. For lower PMD cases, there are almost no system penalties but for high PMD fiber, the penalties are high up to 7 dB in worst case.

EYE DIAGRAM




1
0
10
15
20
25
30
35
40
45

CHAPTER 4

PRACTICAL MEASURMENTS OF PMD

4a. A study OF PMD in real life by measuring PMD of cabled & spooled fibers at Ordinance Cable Factory, Chandigarh using a PMD measuring instrument – WIN PMD

The main source of birefringence in standard telecommunication fibers are twist, non circularity of core, internal stress and bending. The following measurements of cabled and spooled fibers was done at **ORDINANCE CABLE FACTORY, Chandigarh using PMD measuring instrument WIN PMD.**

FIBER	PMD(ps/√km	CABLED/SPOOLED
1	0.54	Cabled
2	.07	
3	.59	
4	.36	
5	.15	
6	.50	
7	.39	
8	.10	Spooled
9	.06	
10	.06	
11	.15	

Measurements show that PMD of cabled fiber is more than spooled which is true because

stress is increased. Measurements are at λ =1550nm
Length of Spooled=2 to 13 Km

Length of Cabled=17 to 24 Km

PMD also varied with different temperature setting.

4b. GENERAL INFORMATION ON WIN-PMD

Product Overview

GN Nettest WIN-PMD is a powerful and easy -to-use Polarization Mode Dispersion (PMD) analyzer. WIN-PMD utilizes a proprietary broadband interferometric technique to provide fast and accurate PMD measurements independent of changes in fiber position. This makes the WIN PMD the ideal tool for both in- situ measurements on installed fiber links and factory measurements at the fiber manufacturing site. WIN PMD covers a wide PMD range. It can accurately characterize PMD from as low as .06ps to 80ps.

The system can operate at both 1.3 um and 1.5um wavelength ranges. The standard WIN PMD uses an external WIDE broadband source featuring dual wavelength E LED light. The win pmd system has it all in one. It features a built in dual wavelength E LED source that allows loop back of fiber under test to the PMD analyzer, ideal for factory measurements.

Measurement Setup:

The figure shows the typical WIN PMD measurement setup with external WIDE source and to the other end to WIN PMD analyzer INPUT port.

STANDARD FEATURES AND BENEFITS

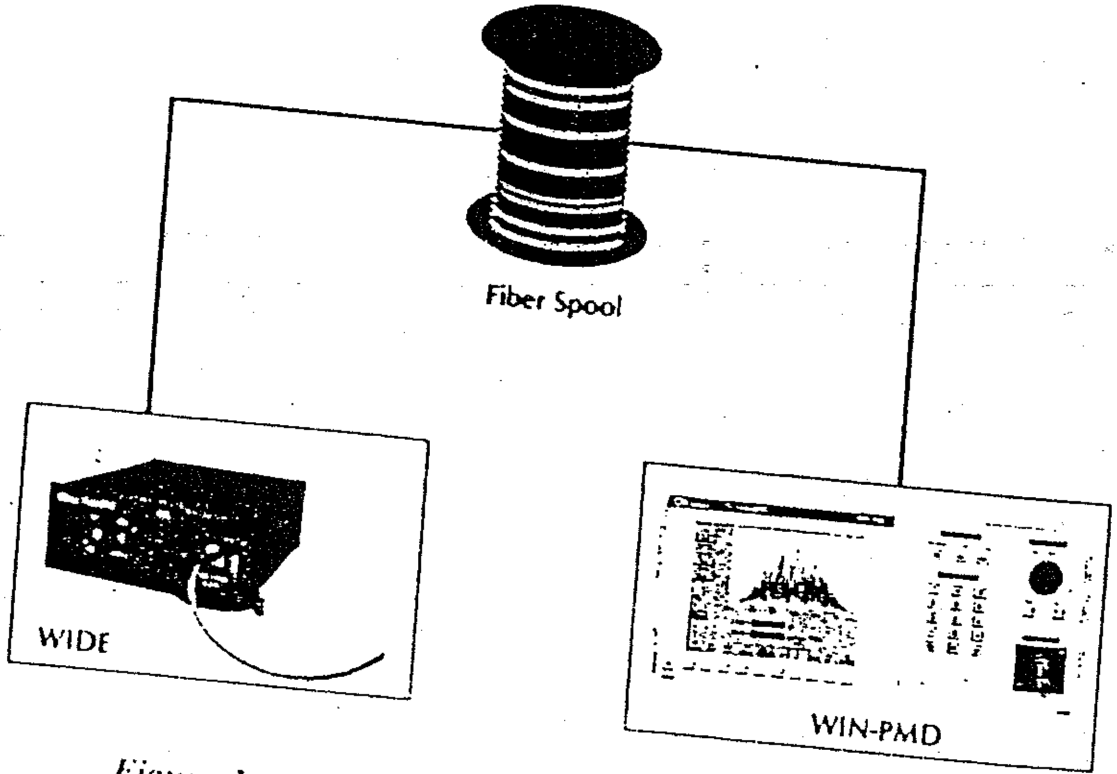


Figure 1 - 1: Example of WIN-PMD measurement setup

The proprietary optical design of WIN PMD analyzer provides a unique range of user benefits.

BENEFIT	DESCRIPTION
Turn key, Stand alone PMD Analyzer	Does not require any communication between the source and analyzer, ideal for PMD measurements of long, installed fiber links.
Fast and accurate PMD characterization	Measurement time takes only a few seconds with both outstanding accuracy and repeatability of 1%
Extended PMD measurement range	Covers all measurement needs from .06ps to 80ps PMD range
A wide choice of broadband sources	Comes with the optional standard external Wide source operating at 1.3 and 1.5 um.
Disturbance free in fiber position	Using a proprietary interferometric technique that makes this PMD Analyzer non independent of position changes of fiber under test.
Single path PMD measurements	Rapid PMD measurements in a single path
Graphical analysis versus time	Performs repeated measurements for a user defined duration and allows graphical analysis of PMD versus time. This allows to determine time dependence of pmd in fibers.

Remote controlled and programmed operation	Remote and programmed operation via IEEE 488.2 or RS 232c interfaces.

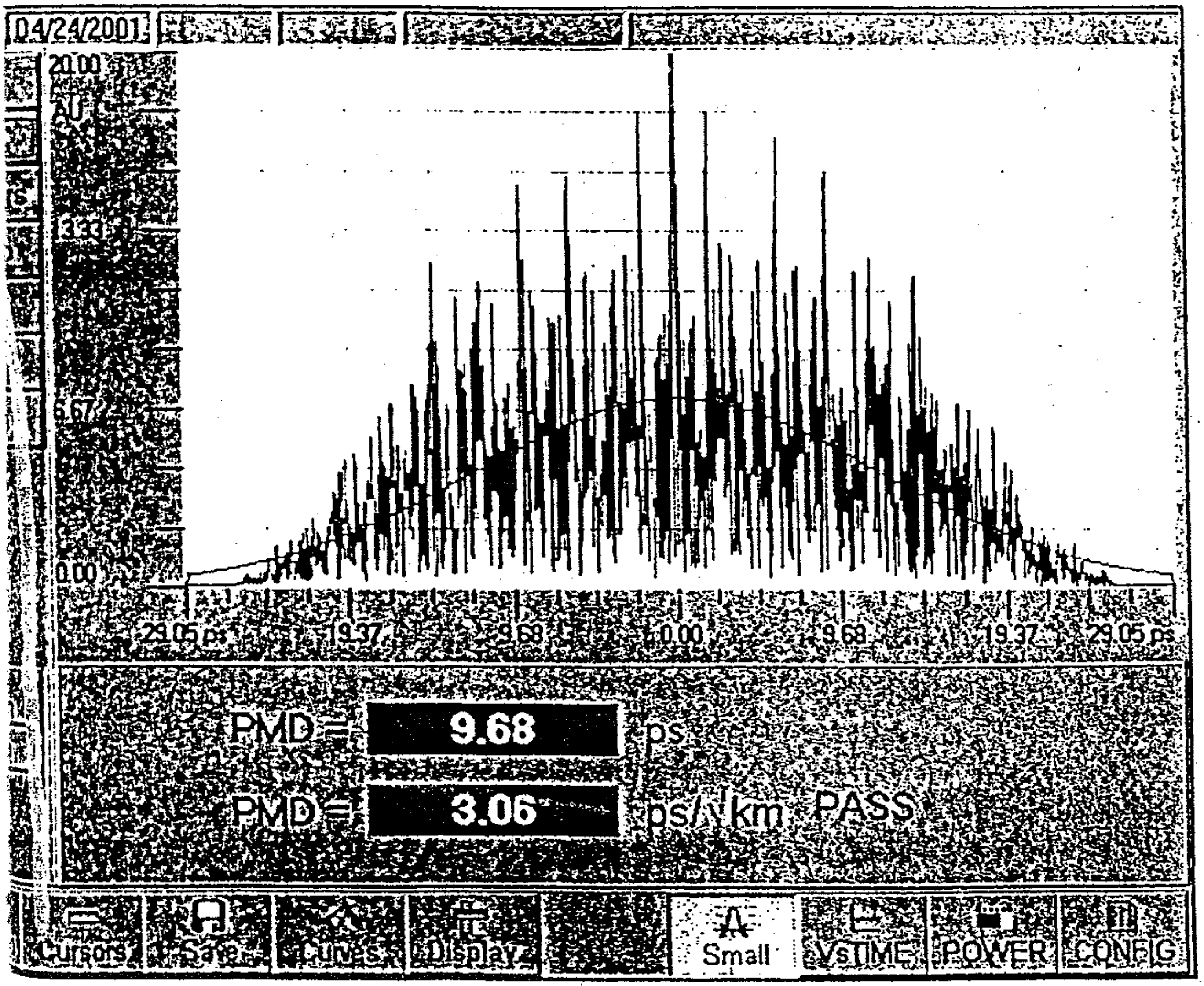
SPECIFICATIONS

Measurement Ranges	
Operating Wavelengths	1.3 and 1.5um
Minimum Measurable PMD	.06ps
Maximum Scanning Range	160ps
Dynamic Range	35 db
Accuracy	1%
Repeatability	1%
Measurement time	30s

DESCRIPTION OF FRONT PANEL FUNCTION KEYS

The front panel is divided into several areas

1. Optical Port Area: Used to connect Optical fiber to PMD Analyzer (Input port)
2. Mode Area: Used to control system operation and to select operating wavelength
3. Data Area: Used to enter numerical values or to cancel operation using numerical keypad
4. Navigator Area: A Rotating Knob selects the various desired functions and parameters to be changed.
5. Graphic Display Area: Includes a large graphic display with 10 function soft keys on the bottom.
6. Disk Drive: The WIN PMD features a standard 3.5" 1.44 MB floppy Disk to save or load data


04/24/2001
20.00
13.33
6.67
0.00
29.05 ps
19.37
9.68
0.00
9.68
19.37
29.05 ps
PMD = 9.68 ps
PMD = 3.06 ps/√km PASS
Cursors
Save
Curves
Display
Small
VsTIME
POWER
CONFIG

CHAPTER 5

PHOTONIC CRYSTAL FIBER

5a. What are Photonic Crystal Fibers

Photonic Crystal Fibers are solid core fibers with uniformly distributed air holes in the cladding. The air holes are generally arranged in a triangular lattice structure. The refractive index of the core is that of silica=1.45 and that of the cladding varies from 1 (air) to 1.45 depending on the diameter of the air holes and pitch(distance between two air holes).More is the Air filling fraction ,less is the refractive index.

The PCF in its normal structure does not show any birefringence because there is no slow or fast axis. Both the modes propagate with equal speed. PCF guides light by corralling it within a periodic array of microscopic air holes that run along the entire length of fiber. Largely through their ability to overcome the limitations of conventional fiber optics for example by permitting low loss guidance of light in a hollow core ,these fibers are proving to have a multitude of important technological and scientific applications spanning many disciplines. The result has been a renaissance of interest in optical fibers and their uses.

A PCF can thus be defined as comprising a bulk material having an arrangement of longitudinal holes, the fiber including a cladding region, and a guiding core, the cladding region having an effective index which varies across fiber cross section in which fiber is capable of supporting A fundamental transverse mode which is substantially confined to guiding core and at least one other transverse mode which is less confined to guiding core.

5b. PCF as Polarization maintaining Fibers

Polarization maintaining fibers (PMFs) are expected to play an important role in high bit – rate fiber transmission system. For example, PMFs can eliminate the influence of Polarization mode dispersion (PMD) to stabilize the operation of optical devices. Currently, PMFs such as PANDA and bow – tie fibers are used for polarization maintaining applications or transmission lines. Their birefringence is due to stress in the core region, and their modal birefringence is ~ 5×10^{-4}.

Photonic crystal fibers (PCFs) are of great interest for optical communication in new wavelength regions and for new optical functional devices. It is also possible to realize highly birefringent fiber with a Photonic structure. Polarization maintaining (PM) PCFs have different air – hoe diameters along two orthogonal axes near the core region , which provide an effective index difference between the two orthogonal polarization modes. It has been shown that their birefringence is of the order of 10^{-3}, which is one order of magnitude larger than that of conventional PMFs and better PM characteristics are expected.

Design of PM-PCF

Figure shows the schematic design and a scanning electron microscope (SEM) photograph of a PM-PCF. To introduce large birefringence into the PCF, we enlarged two of the central air holes. The birefringence arises from the effective refractive index difference between the x and y polarization modes. The diameter of the small and the

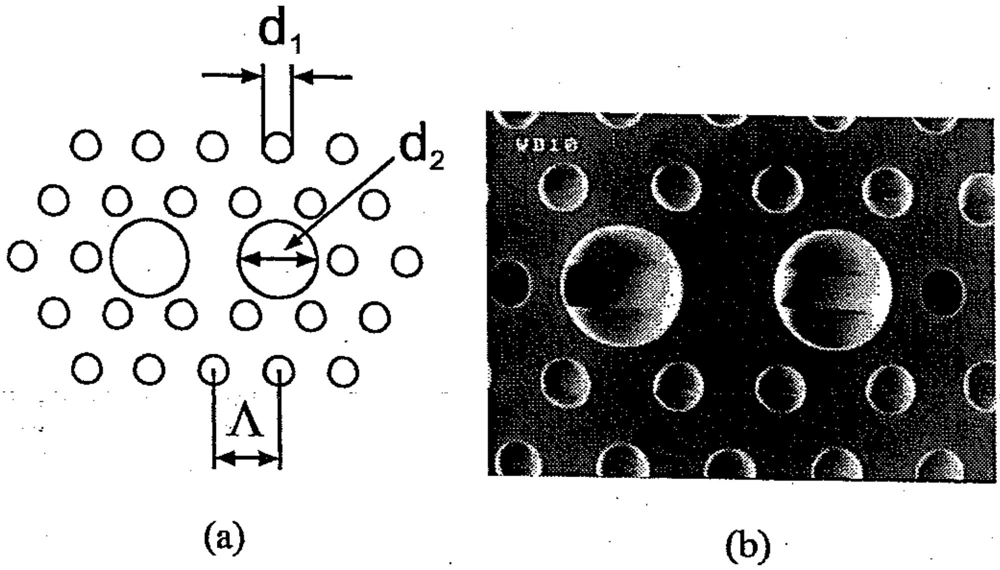


Fig. 1. Schematic view (a) and SEM photograph (b) of a polarization maintaining photonic crystal fiber.

large holes, (d1) and (d2), respectively, and the air hole pitch (Λ) gives the characteristics of PM-PCF. This fiber was designed to have high birefringence and low loss with a simple structure.

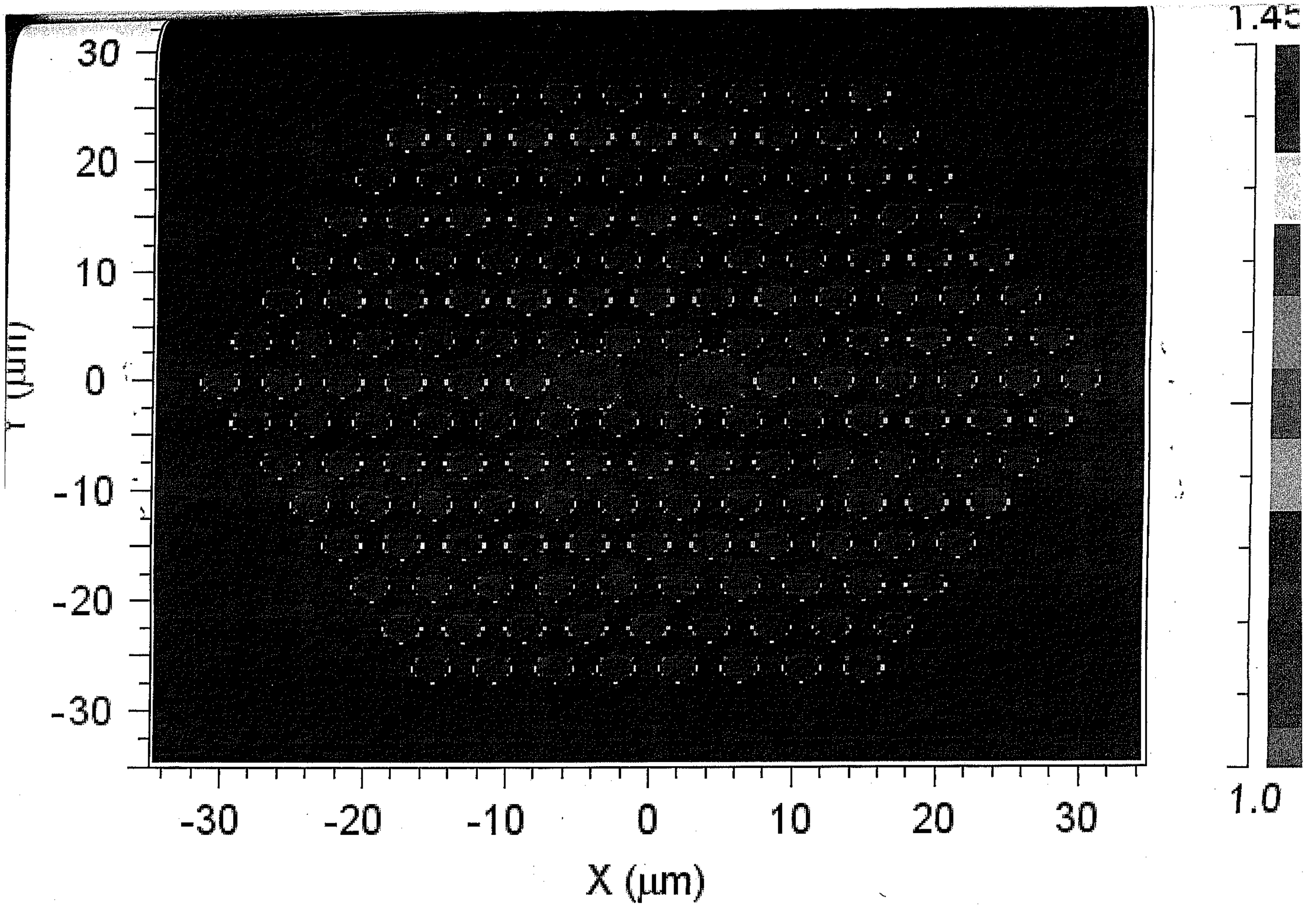
The ratio d_1/d_2 determines the model birefringence of the fiber. When $d_1/d_2 = 1$, the fiber is identical to conventional PCF. There is no birefringence in this structure. The model birefringence increases as d_1/d_2 decreases. This is because the six-fold symmetry is destroyed with a decrease in the d_1/d_2 ratio and the effective refractive index for the orthogonal polarization mode changes. In this experiment, d_1/d_2 was set at 0.40 and the fiber was 1.5 km long. It should be noted that this fiber was single – mode from 1.0 to 1.7μm.

The wavelength dependence of the fiber loss is shown in Fig . The fiber loss at 1550, 1330, and 850 nm were 1.3, 2.0, and 4.2 dB/km, respectively. The Rayleigh scattering coefficient of the PCF and the structural imperfection loss were 1.9 dB/km/(μm)^4 and 1.0 dB/km, respectively. If we can reduce the structural imperfection loss, the fiber loss will be reduced to less than 0.5dB/km which is off the same order as conventional PMF. The maximum loss difference of two orthogonal polarization is 0.27 dB/km. this shows that the large air holes have little influence on PDL.

Polarization characteristic of PM- PCF

The birefringence of PM-PCF could also be obtained by measuring the beat length between the two modes. A birefringence of 1.4 x 10^{-3} is obtained which is three times larger that conventional Panda fiber.

The PMD at 1550 nm was 4.7 ps/m. PMD and birefringence decreases as the wavelength decreases. H cross talk is – 22dB which is better that that of the conventional Panda fiber.



Y (μm)
30
20
10
0
-10
-20
-30
X (μm)
1.45
1.0

By optimizing the fiber parameters we can realize higher birefringence and lower cross talk. This means that we can use this PM-PCF as polarization maintaining optical transmission line.

5c. Calculating Birefringence of PCF

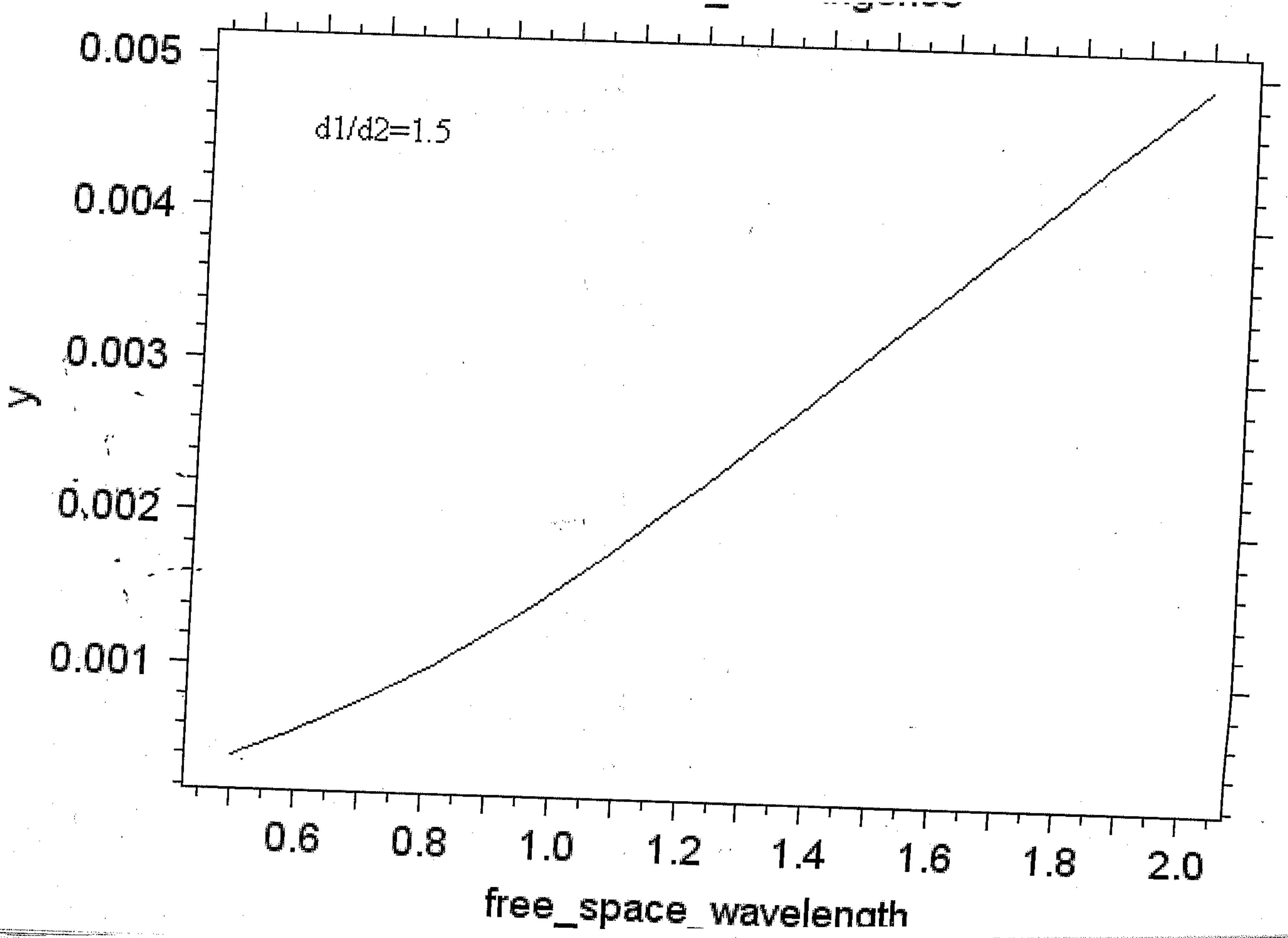
The birefringence of modified structure of PCF has been calculated by the Beam Propagation Method given in the BEAMPROP 7 software by RSOFT. Desired structure of index guided PCF is the first input. Then the various parameters like the wavelength at which birefringence is calculated, ratio of diameters of two holes, pitch etc are fed to the system. Plot of birefringence is then obtained after simulation(as shown in the figure). The details of software too are attached for reference.

BEAM PROPAGATION METHOD

This provides technical information on the simulation methods used in *Beam Propagation* . First , a general background of the BMP algorithm is given .

The objective of Beam Propagation is to provide a general simulation package for computing the propagation of light waves in arbitrary waveguide geometries. This is a complex problem, in general, and several assumptions are made at the outset (many of which are subsequently relaxed). The computational core of the program is based on finite difference beam propagation method as described in references therein. This technique uses finite difference methods to solve the well-known parabolic or paraxial approximation of the Helmholtz equation. In addition, the program uses "transparent" boundary conditions.

The fundamental physical limitation of the above approach results from the parabolic approximation to the Helmholtz equation, which implies a paraxiality condition on the primary direction of propagation. These limitations can be reduced using more accurate


d1/d2=1.5
0.005
0.004
0.003
0.002
0.001
y
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
free_space_wavelength

approximations to the Helmholtz equation. Beam Propagation has the option of implementing this technique, and includes (1,0),(1,1),(2,2),(3,3) and (4,4) Padé approximations.

A second limitation of the above approach results from the assumption of scalar waves, and prevents polarization effects from being considered. *Beam Propogation* Version 2.0, however, introduced several vector beam propogation techniques to overcome this limitation.

The third key limitation of BMP approach described above is that it cannot account for backward reflections since the one-way wave equation on which it is based does not admit both positive and negative traveling waves. Beam Propagation Version 3.0, however, introduced a new bidirectional BPM algorithm, which considers coupled forward and backward traveling waves, and can account for reflection phenomenon, including resonant effects as found in grating structures.

The physical propagation problem requires two key pieces of information :

1. The refractive index distribution, *n*(x,y,z).

2. The input wave field, u(x,y,z=0).

From these, the physics dictates the wave field throughout the rest of the domain, u(x,y,z>0). Naturally, the software provides a way to specify this information; this will be discussed in the following chapters.

The solution algorithm requires additional input in the form of numerical simulation parameters such as:

- A finite computational domain, $\{ x \in (x_{min},x_{max})\}$,$\{y \in (y_{min},y_{max})\}$, and $\{z \in (z_{min},z_{max})\}$.

- The transverse grid sizes, ▲x; and ▲y.

- The longitudinal step size, ▲z.

The software attempts to estimate appropriate values for these parameters, but allow the users to override them. *As with any simulation, confidence in the accuracy of the numerical solution requires experimentation to determine the sensitivity to the numerical parameters.*

Beam Propagation also has capabilities for computing modes, handling nonlinear and anistropic material, and incorporating the effects of electrodes and heaters.

Review of the beam propagation method (BPM)

BPM is the most widely used propagation technique for modeling integrated and fiber optic Photonic devices, and most commercial software for such modeling is based on it.

There are several reasons for the popularity of BPM; perhaps the most significant being that it conceptually straight forward, allowing rapid implementation of the basic technique. This conceptual simplicity also benefits the user of a BPM – based modeling tool as well as the implementer, since an understanding of the results and proper usage of the tool cab be readily grasped by a non – expert in the numerical methods. In addition to its relative simplicity, BPM is generally a very efficient method, and has the characteristic that its computational complexity can, in most cases, be optimal, that is to say the computational effort is directly proportional to the number of the grid points used in the numerical simulation. Another characteristic of the BPM is that he approach is readily applied to the complex geometries without having to develop specialized versions of the method. Further more the approach automatically includes the effects of both guided and extensible, allowing inclusion of most effects of interest e.g. polarization, nonlinearties) by extensions of the basic method that fit within the same overall framework.

Numerous applications of BPM to modeling different aspects of Photonic devices or circuits have appeared in literature. Examples include various wave guiding devices, channel dropping filters, electro – optic modulators, multimode guided devices, ring lasers, optical delay line circuits, novel y - branches, optical interconnects, polarization splitters, multimode interference devices, adiabatic coupler, wave guide polarizers, and polarization rotators. Most of the above reference involve experimental demonstrations of novel devices concepts designed in whole or in part via BPM.

Scalar, paraxial BPM

BPM is essentially a particular approach for approximating the exact wave equation for monochromatic waves, and solving the resulting equations numerically. In this section the basic approach is illustrated by formulating the problem under the restrictions of a scalar field (i.e. neglecting polarization effects) and paraxiality (i.e. propagation restricted to a narrow range of angles). Subsequent sections will describe how these limitations may be removed.

The scalar field assumption allows the wave equation to be written in the form of the well – known Helmholtz equation for monochromatic waves

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} + k(x,y,z)^2\,\phi = 0 \qquad \rightarrow 1$$

Here the scalar electric field has been written as $E(x,y,z,t) = \phi\,(x,y,z)e^{-iwt}$ and the notation $k\,(x,y,z) = k_0\,n\,(x,y,z)$ has been introduced for spatially dependent wave number, with $k_0 = 2\Pi / \lambda$ being the wave number in free space. The geometry of the problem is defined entirely by the refractive index distribution n (x,y,z).

Aside from the scalar assumption, the above equation is exact.Considering that in typical guided wave problem the most rapid variation in the field ϕ is the phase variation due to propagation along the guided axis , and assuming that axis is predominantly along the Z direction, it is beneficial to factor this rapid variation out of the problem by introducing a so called slowly varying field U via the ansatz

$$\phi(x,y,z)=u(x,y,z)e^{ikz} \rightarrow 2$$

Here k is a constant number to be chosen to represent the average phase variation of the field ϕ , and is referred to as reference waveno..The reference waveno. Is frequently expressed in terms of a reference refractive index, n , via $k=k_0 n$ Introducing the above expression into the Helmholtz equation yields the following equation for the slowly vaying field :

$$\frac{\partial^2 u}{\partial z^2} + 2ik\frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - K^{2})u = 0 \rightarrow 3$$

At this point the above equation is completely equivalent to the exact Helmholtz equation, except that it is expressed in terms of u. It is now assumed that the variation of u with z is sufficiently slow so that the first term above can be neglected with respect to the second, this is the familiar slowing varying envelope approximation and in his contest it s also referred to as parabolic approximation the equation is

$$\frac{\partial u}{\partial z} = \frac{i}{2k}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + (k^2 - K^{2})u \right) \rightarrow 4$$

Given an input field $u\,(x,y,z = 0)$, the above equation determines the evolution of the field in the space $z > 0$. The factoring of the rapid phase variation allows the slowly varying field to be represented numerically on a longitudinal grid that can be much coarser than the wavelength for many problems, contributing in part to the efficiency of the technique. The elimination of the second derivative term in z reduces the problem from a second order boundary problem requiring iteration or eigen value analysis, to a first order initial value problem that can be solved by simple integration of above equation along z.

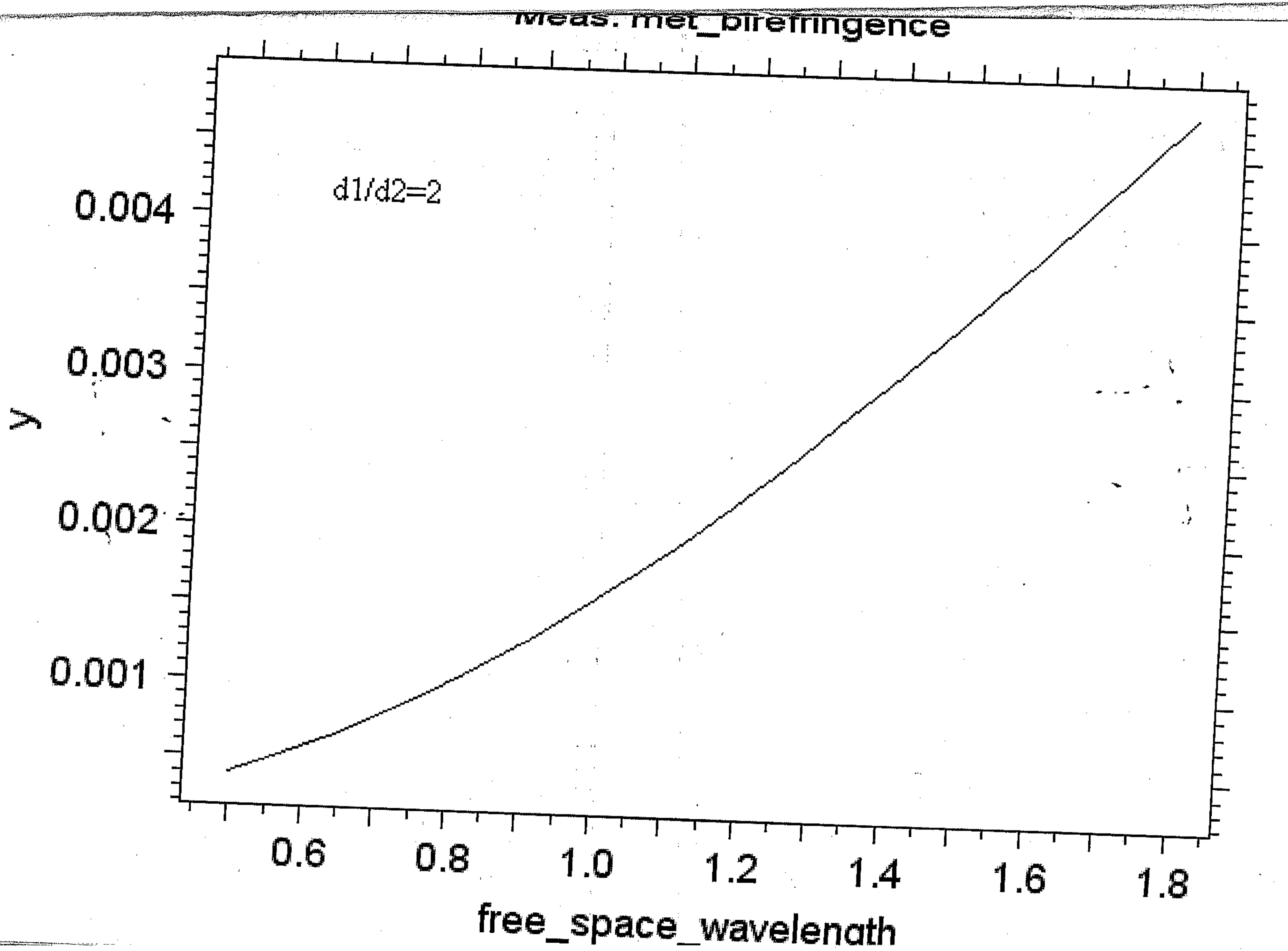
In the finite difference approach the field in the transverse plane is represented only at discrete points on a grid ,and at discrete planes along the propagation direction. Given the discretized field at one Z plane, the goal is to derive numerical equations that determine the field at next Z plane. This elementary propagation step is then repeated to determine the field throughout the structure.

Let u_i^n denote the field at transverse point I and longitudinal plan n and assume the grid points and plan are equally spaced by x and z respectively. In the Crank – Nicholson method equation 4 is represented at the mid plane between the known plan n and unknown plan n +1 as follows

$$\frac{u_i^{n+1} + u_i^n}{\Delta z} = \frac{i}{2k}\left(\frac{\delta^2}{\Delta x^2} + \left(k\,(x_i\,,\,z_{n+1/2})^2 - K^{-2}\right)\right)\frac{u_i^{n+1} + u_i^n}{2} \quad \rightarrow 5$$

The above equation can be rearranged in to the form of a standard tridiagonal matrix equation for the unknown field ui n + 1 in terms of known quantity, as

$$a_i\,u_{i-1}^{n+1} + b_i\,u_i^{n+1} + c_i\,u_{i-1}^{n+1} = d_i \quad \rightarrow 6$$


Meas. met_birefringence
d1/d2=2
0.004
0.003
0.002
0.001
y
0.6
0.8
1.0
1.2
1.4
1.6
1.8
free_space_wavelength

Since the field only be represented on a finite computational domain, when the above equation is applied at the boundary points $i = 1$ and N it refers to unknown quantities outside the domain. A commonly used boundary condition is the so called transparent boundary condition. The basic approach is to assume that near the boundary the field behaves as an out going plane wave which allows the field at the boundary point to be related to adjacent interior point. The TBC is generally very effective in allowing radiation to freely escape the computational domain.

5d. Calculating PMD of PCF

The PMD of modified structure of PCF has been calculated by the formula given below.

PMD = Calculated Birefringence x √ Coupling length x √ total length of the fiber

$$= 4\times10^{-3} \times \sqrt{10} \times \sqrt{1500} = 4.7 \text{ ps / m}$$

5e. Comparison of PCF with other Fibers

The ordinary fiber has birefringence of the order of 10^-6 .For some applications it is desirable that fibers transmit light without changing its state of polarization,. A large amount of birefringence is introduced intentionally in these fibers through design modifications so that small changes in birefringence are masked by it and light travels without changing its state of polarization. One is making the core elliptical in shape. The birefringence achieved is 10^-5.Another type is making stress induced fibers by inserting two rods of borosilicate glass on opposite sides during preform stage. Value of birefringence depends on amount of stress induced and such fibers are called BOW TIE or PANDA Fibers. The birefringence achieved is 10^-4.

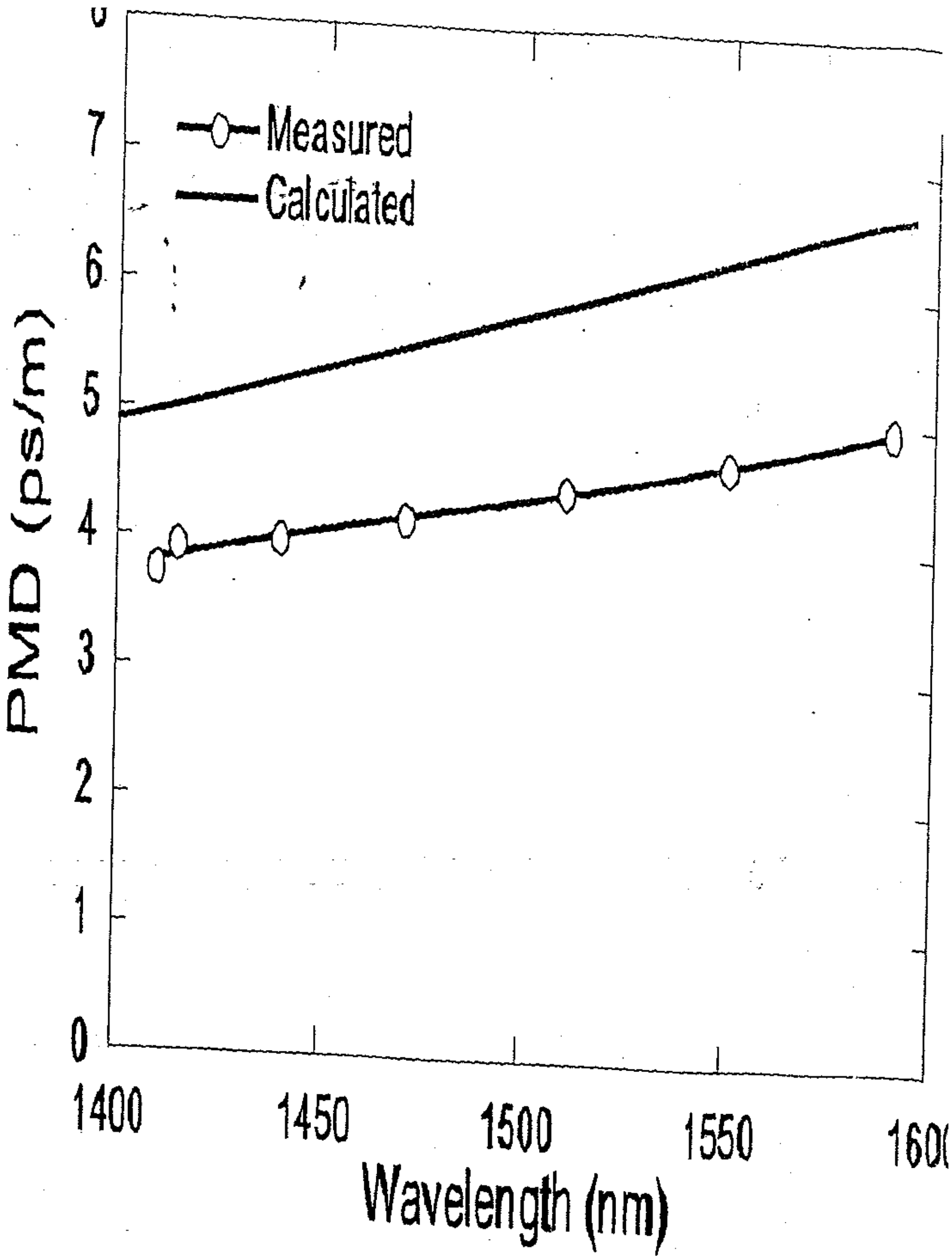


Fig. 4. Wavelength dependence of PM-PCF polarization mode dispersion .

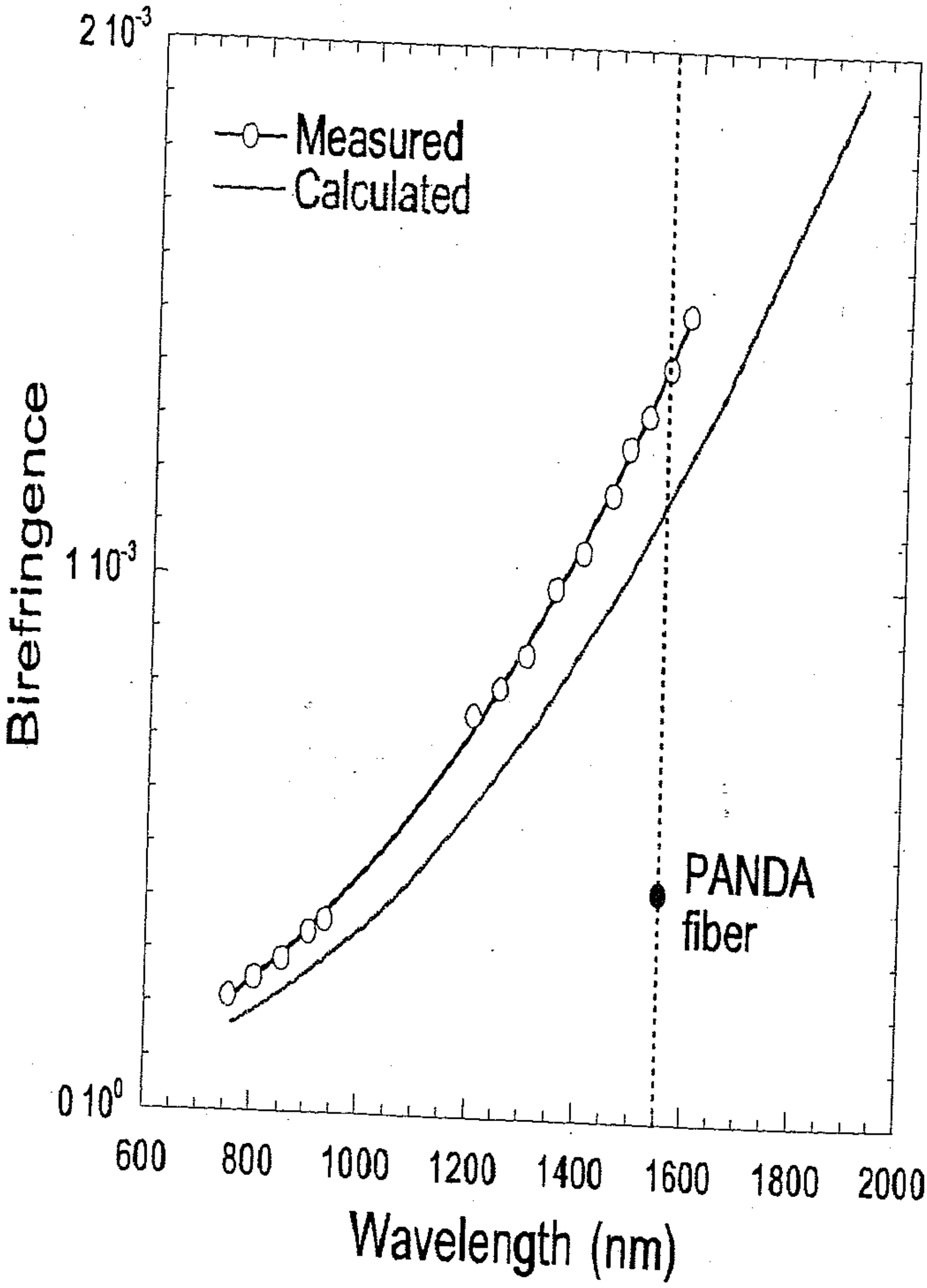


Fig.3. Wavelength dependence of PM-PCF birefringence. The solid curve shows the calculated results.

An ordinary PCF does not show any Birefringence, but if the structure of PCF is modified, or example the core is made elliptical by removing two air holes on opposite side of core or by enlarging size of two holes near the core, A high value of birefringence is achieved=10^-3.Such high birefringence makes it more suitable to be used as Polarization Maintaining Fiber compared to other fibers.

CHAPTER 6

POLARIZATION DIVISION MULTIPLEXING

6a. PMD Induced Transmission Penalties in Polarization Multiplexed transmission

Polarization Multiplexing doubles the capacity of a wavelength channel and the spectral efficiency by transmitting two signals via orthogonal states of polarization. Hence doubling fiber capacity through polarization multiplexing has been very promising in optical communication.

Although polarization multiplexing is considered interesting for increasing the transmitted capacity, it suffers from decreased Polarization Mode Dispersion tolerance, due to polarization sensitive tolerance used to separate the polarization multiplexed channels.
In this section ,the interaction between PMD, chromatic dispersion and non linear transmission impairments are considered.
PMD Penalties In POLMUX Transmission:

The random birefringence in optical fibers induces an unpredictable rotation to the SOP. Because POLMUX transmission makes use of both the sops ,this unpredictable rotation must be corrected in order to avoid misalignment penalties with the polarization sensitive receiver. In the presence of Differential Group Delay ,the delay between Principal States of Polarization results in change of SOP at the leading and falling edge of the pulse. SOP is different when two 1's are transmitted than when a 1 and a 0 are transmitted.

Non Linear Penalties In POLMUX Transmission:

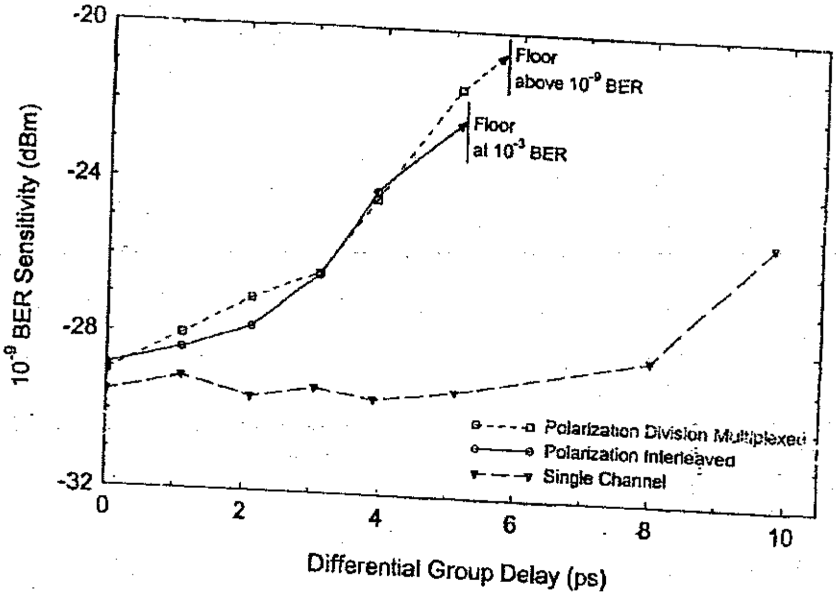
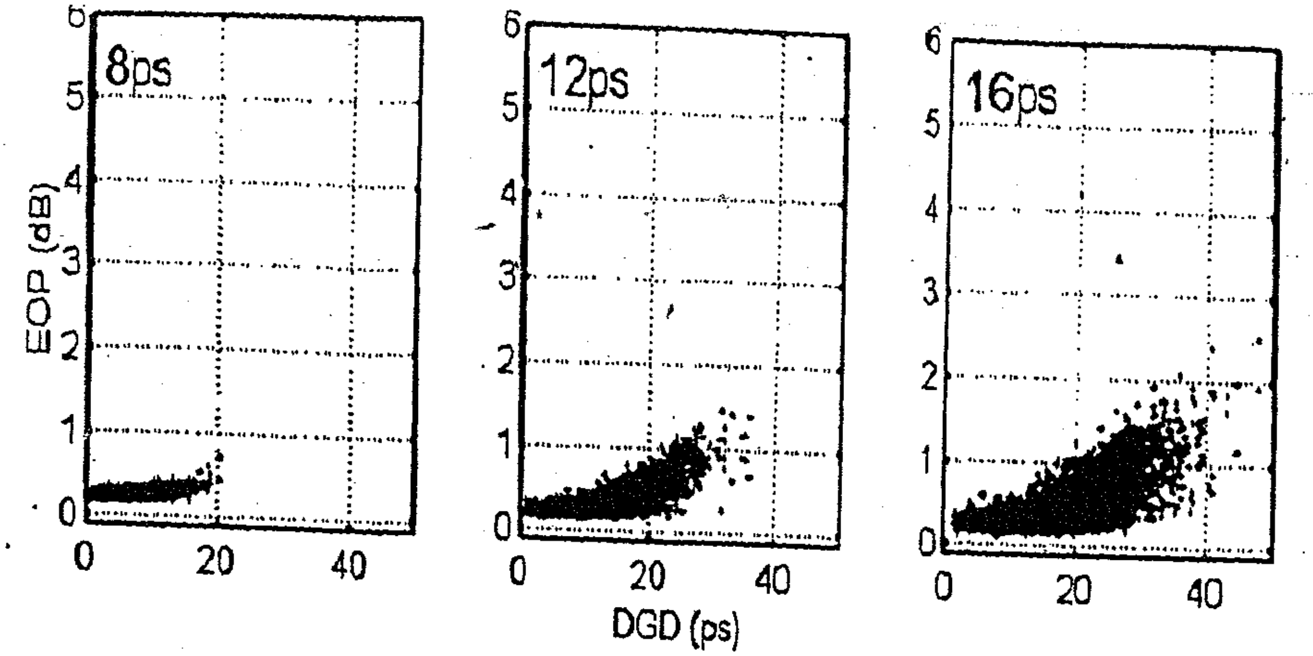
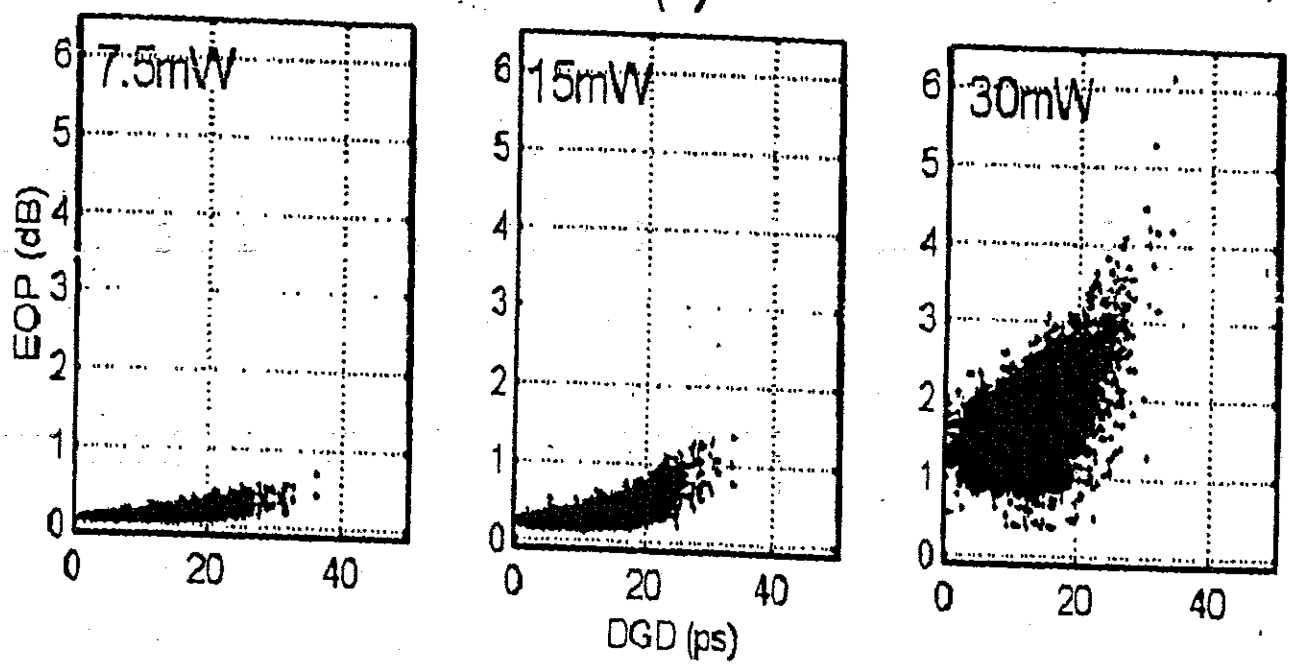


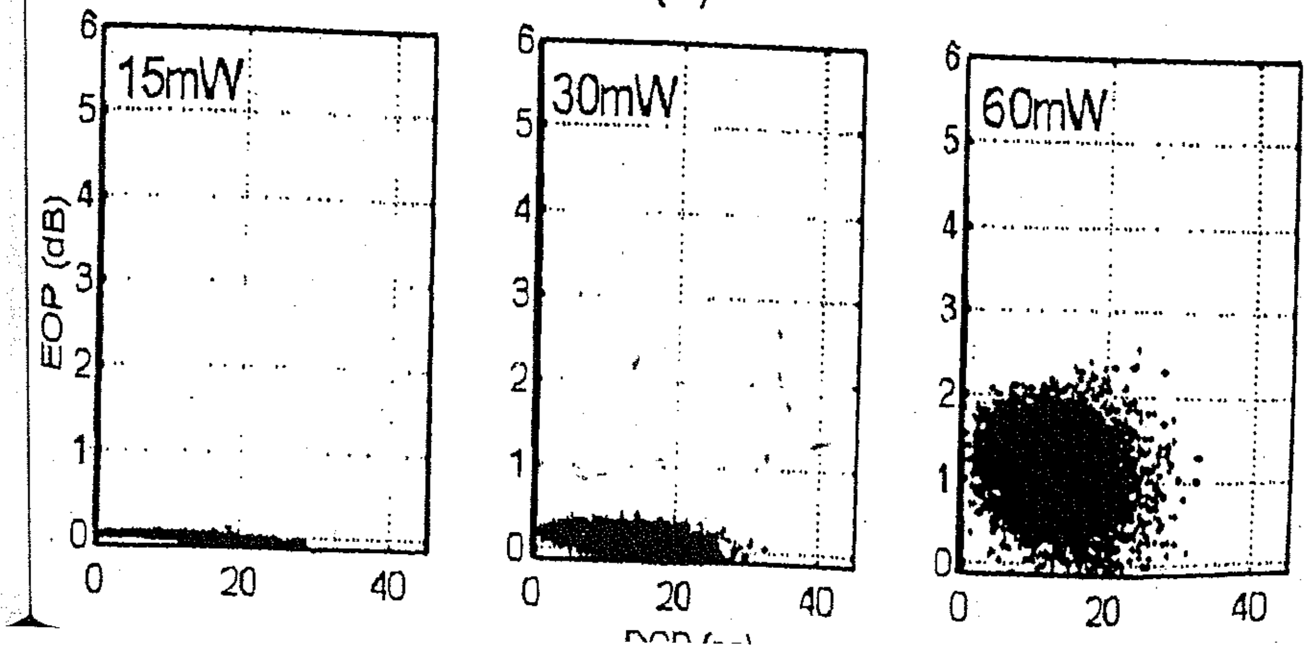
Fig. 4. Sensitivity at 10^{-9} BER for six DGD values based on BER measurements at 40-Gb/s NRZ for interleaving and PDM. Single-channel sensitivity is shown for comparison.


8ps
12ps
16ps
EOP (dB)
DGD (ps)

(c)


7.5mW
15mW
30mW
EOP (dB)
DGD (ps)

(d)


15mW
30mW
60mW
EOP (dB)

In POLMUX transmission ,coherent cross talk can be a result of influence of fiber non linearity in the absence of DGD. Non linear interaction between both polarization channels of a single wavelength channel results in a xPM like effect that induces coherent coupling between polarization channels. depending on the SOP, the power in both the PSPs is different resulting in non linear effects. PolMux transmission shows a much steeper increase in Eye Opening Penalty than for increasing average PMD. Thus it can be concluded that for high launch powers, the influence between DGD and Fiber Non Linearity dominates the transmission penalties in PolMUX transmission than due to DGD alone.

6b. High speed Bi-directional Polarization Division Multiplexed Optical transmission in Polarization Maintaining Photonic Crystal Fiber

Polarization Maintaining Fibers are expected to play an important role in high bit rate transmission system. For example PMFs can eliminate the influence of Polarization Mode Dispersion.

PCFs are of great interest for optical communication in new wavelength regions and for new optical functional devices. .It is also possible to realize highly birefringent fiber with a Photonic Crystal Fiber by enlarging air hole diameter along two orthogonal axis near core region which provide an effective index difference between the two orthogonal polarization modes. Their birefringence is of one magnitude larger than conventional PANDA fibers and better PM characteristics loss are expected.

In the reference () 10Gbps transmission of optical signals Bidirectionally through the PM-

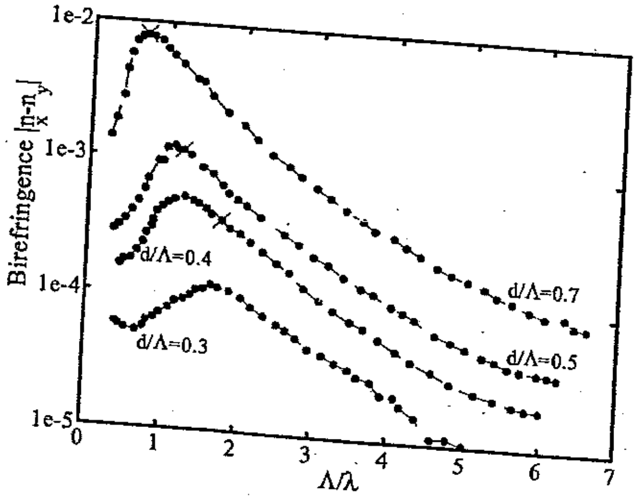


Fig. 4. Calculated birefringence signature of near-elliptic core PCF as a function of Λ/λ with d/Λ as a parameter.

PCF has been reported. The ratio d1/d2 was set at 0.4 and fiber was 1.5 km long. The Loss at 1550 was reported to be 1.2db/Km.The birefringence was measured by observing beat length which matches with our calculated value=1.4*10^-3 at 1550nm. The PMD observed was 4.7ps/m.

The cross talk at 1.5 km long was –22db,better than conventional PANDA fiber. The Power penalty after transmission was less than .2 db.

CONCLUSION

It is concluded that Polarization Mode Dispersion is a big obstacle for optical communication. PMD therefore is a hindrance to Polarization division multiplexing, an alternate for increasing spectral efficiency .Suitability of Photonic crystal fibers for polarization division multiplexing has been proved.

FURTHER SOPE OF WORK

While Studying the suitability of PM_PCF for bi-directional polmux transmission it was observed that GVD had increased tremendously (66ps/km/nm).A higher bit rate would be possible if GVD could be controlled. Further work could be done in exploring transmission of solitons through PCF.

The PCF structure could also be modified to make core elliptic and also increase the size of two holes near the core. This could also result into a highly birefringent polarization maintaining fiber.

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