Differential Mode Group Delay (DMGD) in Few Mode Fibers (FMF)

Microwave Interferometric Technique for Characterizing Few Mode Fibers

Abstract—We propose and experimentally demonstrate a simple and accurate technique for measuring differential mode group delay (DMGD) in few mode fibers (FMF). A frequency-swept microwave signal is modulated on a filtered optical incoherent source. The microwave signals carried on different fiber modes experience different time delays and interfere with each other in the photodetector. Optical interference between propagating fiber modes is avoided by the use of an incoherent optical source. A mathematical model is established to analyze the interference pattern and extract the DMGD values. A 456-m two-mode fiber and a 981-m FMF, which supports four LP modes, are measured. The measurement covers the whole C-band and the results coincide well with those obtained by the time-of-flight method and the numerical simulations. A precision of ±0.002 ps/m is achieved. [1]

Introduction:

Few mode fibers (FMF) have been recently employed in mode division multiplexing (MDM) which is considered to be a promising solution for scaling the data-carrying capacity of networks. Differential mode group delay (DMGD) is an important parameter of FMFs and should be carefully chosen in fiber design.

Project Layout

Since the core has a higher index of refraction than the cladding, light will be confined to the core if the angular condition for Total Internal Reflectance is met. The fiber geometry and composition determine the discrete set of electromagnetic fields, or fiber modes, which can propagate in the fiber. Figure 1 (a) illustrates a step-index fiber having a uniform core of radius (a) with one index of refraction (n_{core}), and a uniform cladding with a smaller index of refraction ($n_{cladding}$). The OptiFiber profile layout is shown in Fig. 1 (b).

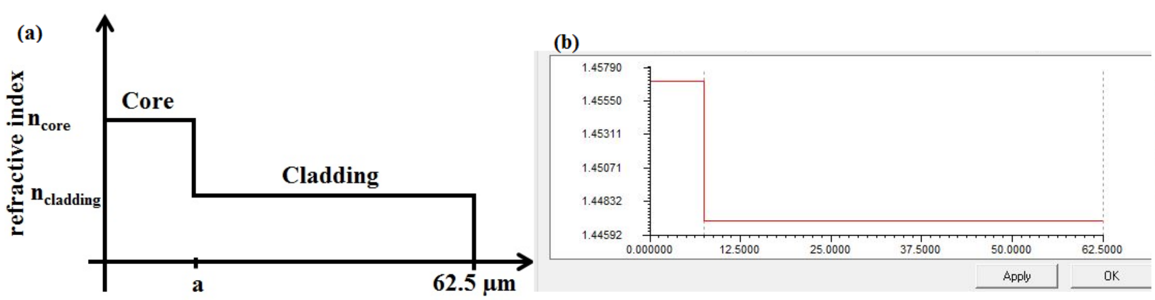


Figure 1: (a) A cross section plane view through a step-index fiber and (b) OptiFiber Profile layout.

FMF Design

The fiber parameter (V) that plays an important role in determining the cut-off condition of the propagating modes is given by:

$$V = \frac{2\pi a}{\lambda} NA,$$

where λ is the operating wavelength and NA is the numerical aperture. The numerical aperture is a measure of the acceptance angle of the fiber. It is very important because it determines how strongly a fiber guides light, and so how resistant it is to bend-induced losses. It is given by:

$$NA = \sqrt{n_{core}^2 - n_{cladding}^2}.$$

The following table summarizes the propagating modes according to the fiber parameter (V).

Fiber parameter (V)	Modes
V < 2.405	LP_{01}
2.405<V<3.832	LP_{01}, LP_{11}
3.832<V<5.136	LP_{01}, LP_{11}, LP_{02}, LP_{21}
5.136<V<5.520	LP_{01}, LP_{11}, LP_{02}, LP_{21}, LP_{31}
5.520<V<6.380	LP_{01}, LP_{11}, LP_{02}, LP_{21}, LP_{31}, LP_{12}

Table 1: The existing propagating modes for a given range of V parameter.

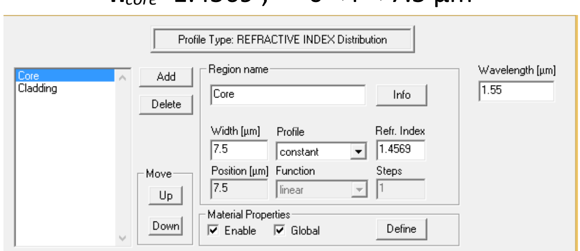
1. FMF supports 2-modes

Numerical simulations were performed assuming a step index profile with a *NA* of 0.17 and core diameter of 15 µm [1].

Design Fiber Profile:

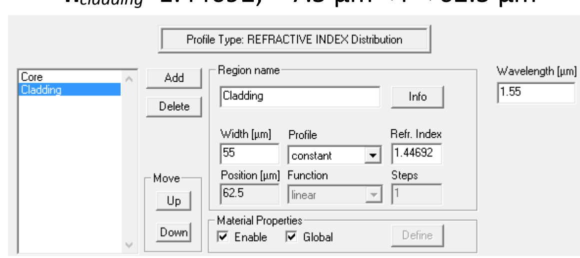
Core refractive index

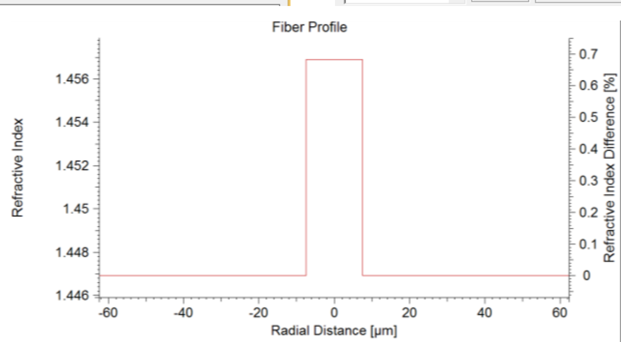
n_{core}=1.4569 ; 0 < r < 7.5 µm



Cladding refractive index

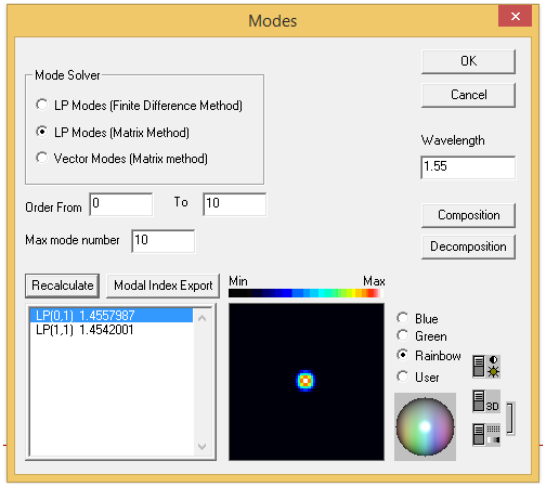
$n_{cladding}$=1.44692; 7.5 µm < r < 62.5 µm





Calculating Fiber Modes:

From the parameters of this fiber the V parameter is, V=3.78, which determines that the fiber should support 2 modes. The numerical calculations show that indeed the fiber supports two guided modes: LP_{01}, LP_{11}.



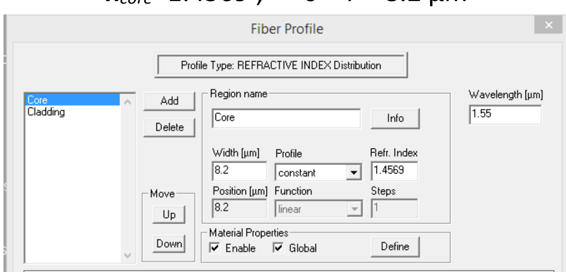
1. FMF supports 4-modes

Numerical simulations were performed assuming a step index profile with a *NA* of 0.116 and core diameter of 16.4 µm [1].

Design Fiber Profile:

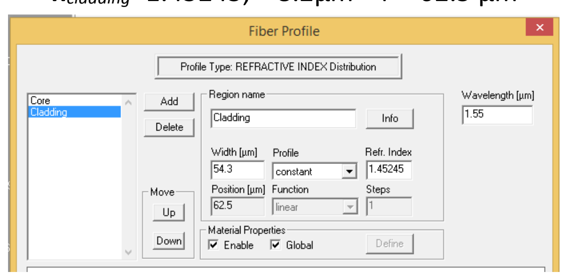
Core refractive index

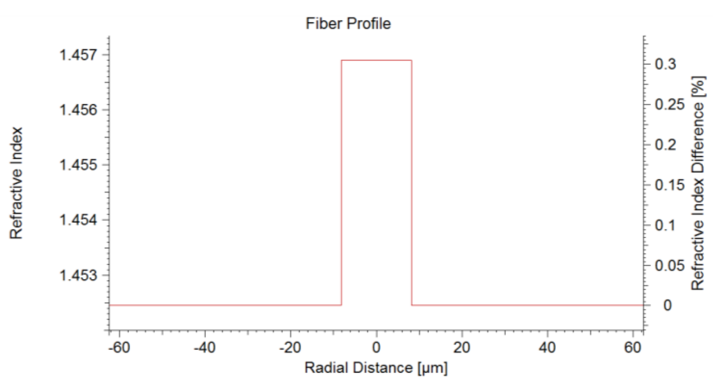
n_{core}=1.4569 ; 0 < r < 8.2 µm



Cladding refractive index

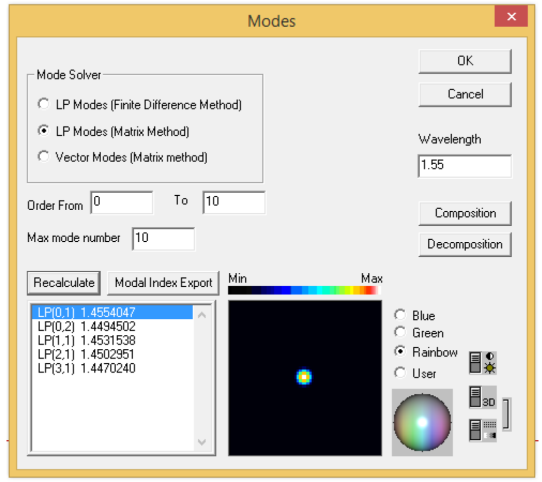
$n_{cladding}$=1.45245; 8.2µm < r < 62.5 µm





Calculating Fiber Modes:

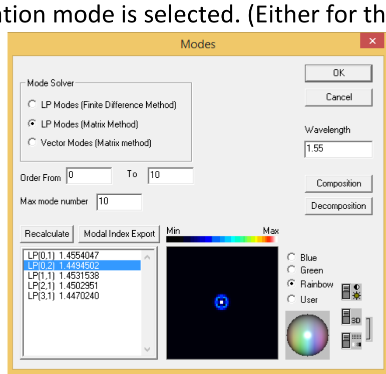
From the parameters of this fiber the V parameter is, V=5.16, which determines that the fiber should support 5 modes. The numerical calculations show that indeed the fiber supports five guided modes: LP_{01}, LP_{11}, LP_{02}, LP_{21} and LP_{31}. LP_{31} is not further analyzed in the simulations because it is very close to cut-off conditions.

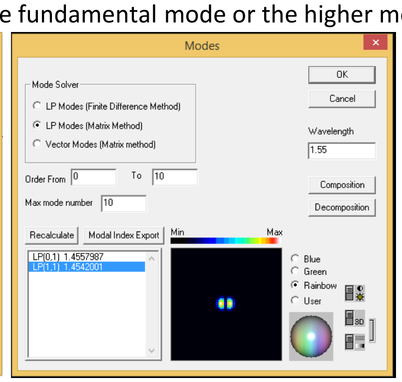


Results

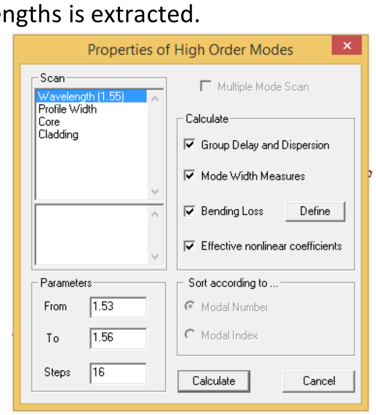
In order to calculate Differential Mode Group Delay (DMGD) at different wavelengths:

1- The propagation mode is selected. (Either for the fundamental mode or the higher modes).



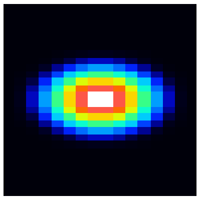


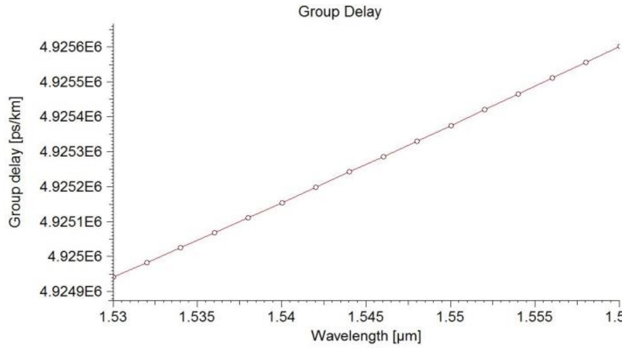
2- The group delay at different wavelengths is extracted.

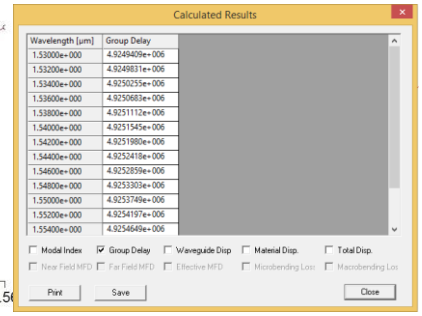


<u>FMF supports 4-modes</u>

Fundamental
Mode LP_{01}

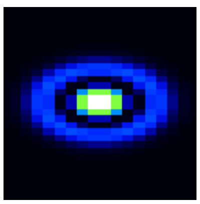


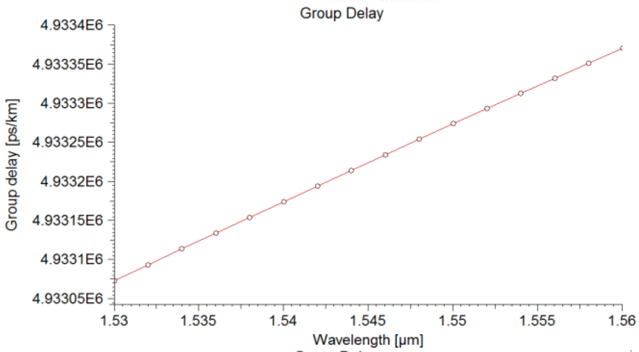


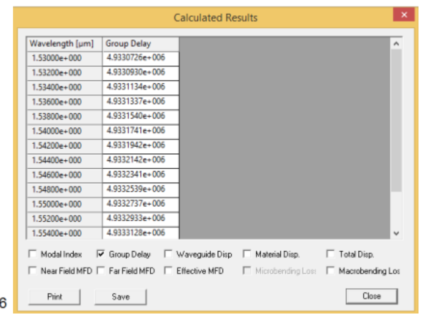


Wavelength [µm]	Group Delay
1.53000e+000	4.9249409e+006
1.53200e+000	4.9249831e+006
1.53400e+000	4.9250255e+006
1.53600e+000	4.9250683e+006
1.53800e+000	4.9251112e+006
1.54000e+000	4.9251545e+006
1.54200e+000	4.9251980e+006
1.54400e+000	4.9252418e+006
1.54600e+000	4.9252859e+006
1.54800e+000	4.9253303e+006
1.55000e+000	4.9253749e+006
1.55200e+000	4.9254197e+006
1.55400e+000	4.9254649e+006

Higher
Mode LP_{02}

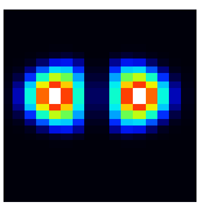


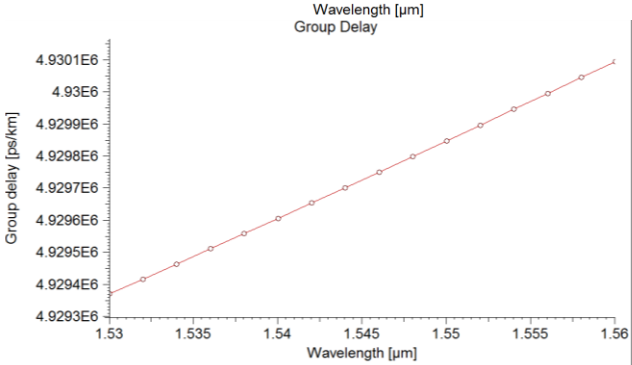


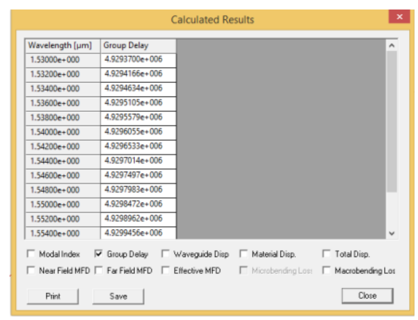


Wavelength [µm]	Group Delay
1.53000e+000	4.9330726e+006
1.53200e+000	4.9330930e+006
1.53400e+000	4.9331134e+006
1.53600e+000	4.9331337e+006
1.53800e+000	4.9331540e+006
1.54000e+000	4.9331741e+006
1.54200e+000	4.9331942e+006
1.54400e+000	4.9332142e+006
1.54600e+000	4.9332341e+006
1.54800e+000	4.9332539e+006
1.55000e+000	4.9332737e+006
1.55200e+000	4.9332933e+006
1.55400e+000	4.9333128e+006

Higher
Mode LP_{11}

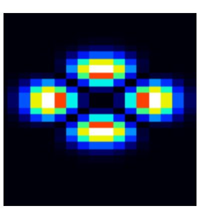


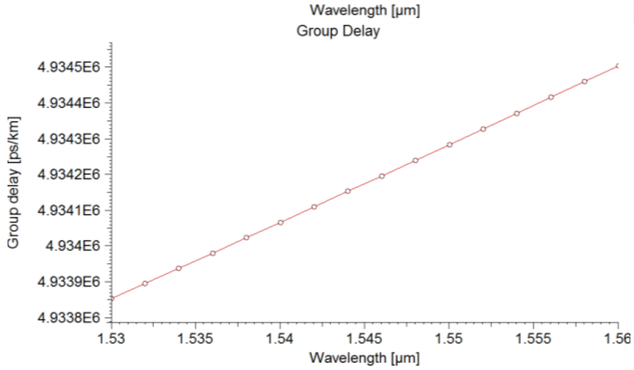


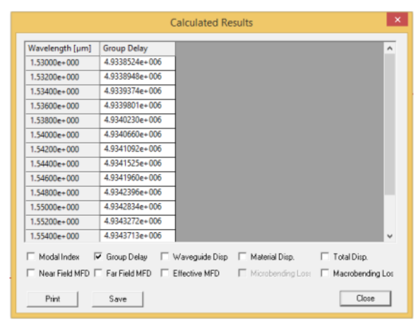


Wavelength [µm]	Group Delay
1.53000e+000	4.9293700e+006
1.53200e+000	4.9294166e+006
1.53400e+000	4.9294634e+006
1.53600e+000	4.9295105e+006
1.53800e+000	4.9295579e+006
1.54000e+000	4.9296055e+006
1.54200e+000	4.9296533e+006
1.54400e+000	4.9297014e+006
1.54600e+000	4.9297497e+006
1.54800e+000	4.9297983e+006
1.55000e+000	4.9298472e+006
1.55200e+000	4.9298962e+006
1.55400e+000	4.9299456e+006

Higher
Mode LP_{21}



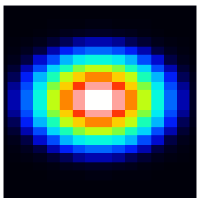


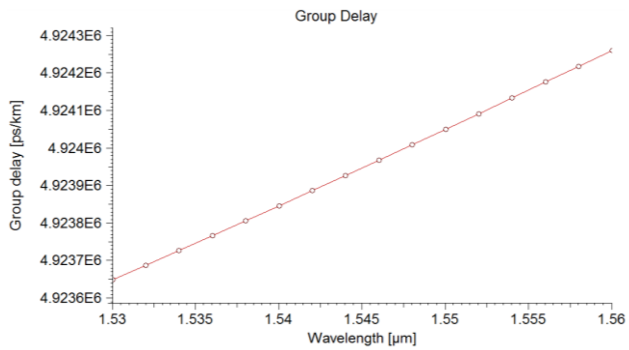


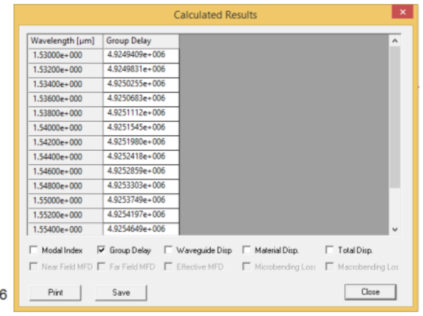
Wavelength [µm]	Group Delay
1.53000e+000	4.9338524e+006
1.53200e+000	4.9338948e+006
1.53400e+000	4.9339374e+006
1.53600e+000	4.9339801e+006
1.53800e+000	4.9340230e+006
1.54000e+000	4.9340660e+006
1.54200e+000	4.9341092e+006
1.54400e+000	4.9341525e+006
1.54600e+000	4.9341960e+006
1.54800e+000	4.9342396e+006
1.55000e+000	4.9342834e+006
1.55200e+000	4.9343272e+006
1.55400e+000	4.9343713e+006

FMF supports 2-modes

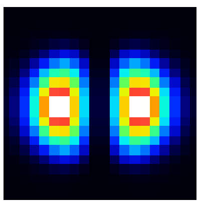
Fundamental
Mode LP_{01}

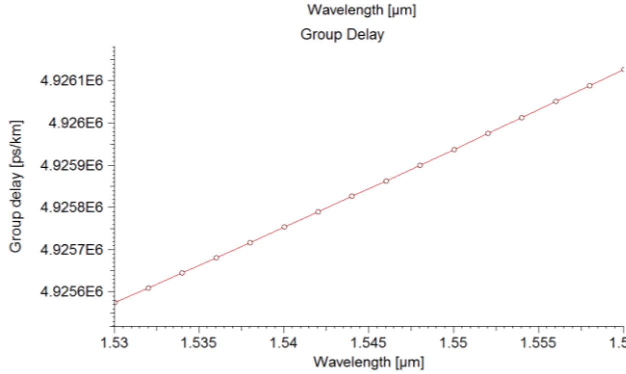


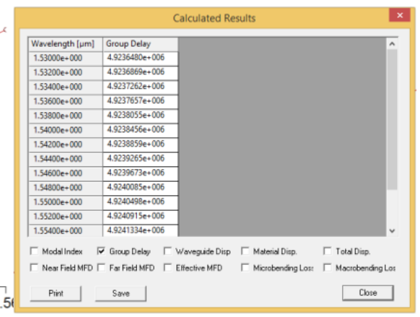




Higher
Mode LP_{11}







3- DMGD are then calculated between each higher mode and the fundamental mode.

λ (μm)	**FMF supports 4-modes**			**FMF supports 2-modes**
	LP_{11}–LP_{01} (ps/m)	LP_{02}–LP_{01} (ps/m)	LP_{21}–LP_{01} (ps/m)	LP_{11}–LP_{01} (ps/m)
1.530	4.424	8.068	8.886	1.926
1.532	4.429	8.046	8.886	1.922
1.534	4.433	8.023	8.886	1.918
1.536	4.437	8.000	8.886	1.915
1.538	4.442	7.977	8.886	1.911
1.540	4.446	7.953	8.885	1.907
1.542	4.450	7.929	8.884	1.903
1.544	4.455	7.905	8.884	1.899
1.546	4.459	7.880	8.883	1.895
1.548	4.463	7.855	8.882	1.891
1.550	4.467	7.829	8.881	1.887
1.552	4.471	7.803	8.880	1.883
1.554	4.475	7.777	8.878	1.879
1.556	4.480	7.750	8.877	1.875
1.558	4.484	7.723	8.875	1.871
1.560	4.488	7.696	8.873	1.867

4- DMGD is finally plotted at different wavelengths.

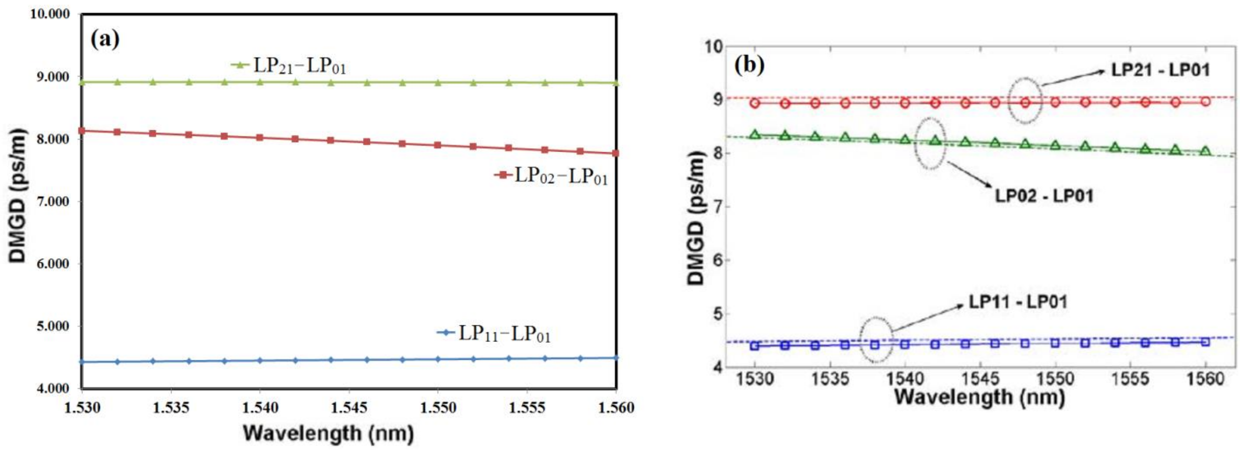


Figure 2: (a) Simulated DMGD for four mode fiber and (b) Experimental results [1].

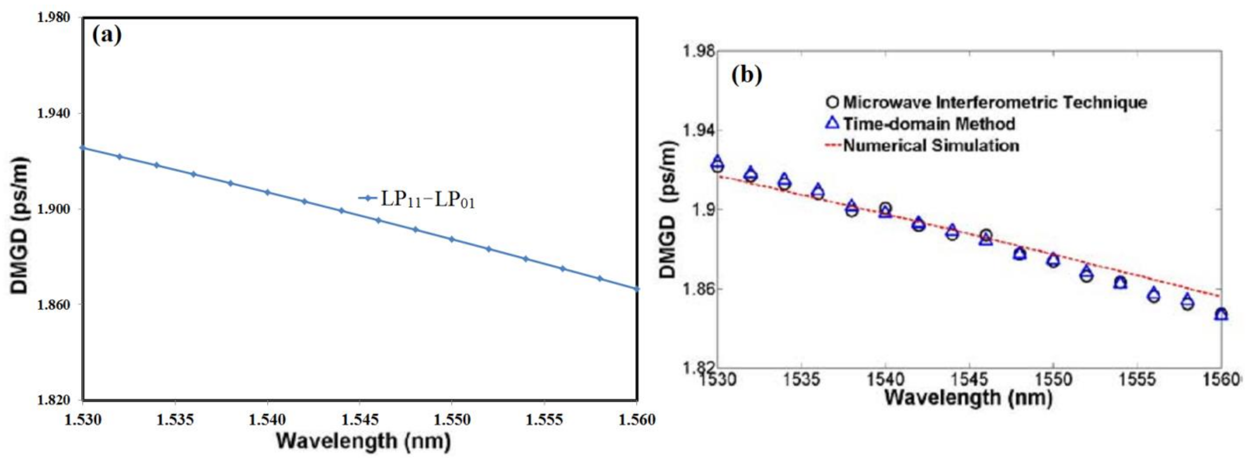


Figure 3: (a) Simulated DMGD for two mode fiber and (b) Experimental results [1].

Figures 2 and 3 demonstrate that the experimental results [1] agree with the simulated DMGD for the two and four mode fibers.

References

[1] Lixian Wang, Cang Jin, Younès Messaddeq, and Sophie LaRochelle, "Microwave Interferometric Technique for Characterizing Few Mode Fibers," IEEE PHOTONICS TECHNOLOGY LETTERS, **26** (17), 1695 -1698, 2014.