# Accurate measurement of total mode coupling in few mode fibers (FMFs) based on a modified spatial and spectral resolved ($S^2$) imaging system

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*Abstract*—**The accurate measurement of total mode coupling in FMFs was achieved by a modified $S^2$ imaging system with electromagnetic interference (EMI) shielding. The measurement accuracy of total discrete and distributed mode coupling was improved by 1.41dB and 2.67dB, respectively.**

***Keywords-mode coupling; $S^2$ imaging;FMF;***

## I. INTRODUCTION

As a novel specialty optical fiber, FMF has been widely applied into lasers and sensors in addition to space division multiplexing (SDM)[1,2]. As the specific impairment in FMF, mode coupling inevitably affects its applications, such as the multiple-input-multiple-output (MIMO) complexity of the SDM system, mode dependent loss (MDL) of the FMF sensors [3,4]. Therefore, an effective method developed to measure mode coupling in FMFs become increasingly necessary. Among various techniques utilized to test certain properties of fibers, $S^2$ imaging shows its advantages in the measurement of mode coupling[5]. However, its measurement accuracy was severely affected with the EMI in the actual $S^2$ imaging system.

In this paper, a modified $S^2$ imaging system with EMI shielding was proposed so as to obtain an accurate measurement of mode coupling in FMFs. From comparison of results obtained by standard (with EMI) and modified $S^2$ imaging system (without EMI), we concluded that the measurement accuracy of total discrete and distributed mode coupling was improved by 1.41dB and 2.67dB.

## II. THEORY AND EXPERIMENTAL SET-UP

Mode spectral interference due to the differential mode group delay (DMGD), which was utilized by $S^2$ imaging technique to characterize the fiber under test (FUT), has been reported in Ref [6]. At the beginning of FUT, modes are completely excited, including fundamental mode (FM) and higher order modes (HOMs). Thus, the output intensity at the end of the fiber can be expressed by the following equation.

$$I(x,y,z=L,\omega_0+\Omega)=I_{01}\left|\psi_{01}(x,y)\right|^2+\sum_{mn}2\,\mathrm{Re}\left\{A_{01}A_{mn}^{*}\psi_{01}(x,y)\psi_{mn}^{*}(x,y)\right\}\cos\left(\delta\tau_{\omega_0,mn}\cdot\Omega\right)\cos\left(\delta\varphi_{mn}\right) \quad (1)$$

Here, I is the intensity at any point ($x$, $y$) on the fiber transverse plane. $L$ is the length of FUT while $\phi$ and $A$ are the field distribution and amplitude of the modes propagating in the FUT. $\delta\tau$ is the DMGD between FM and HOMs.

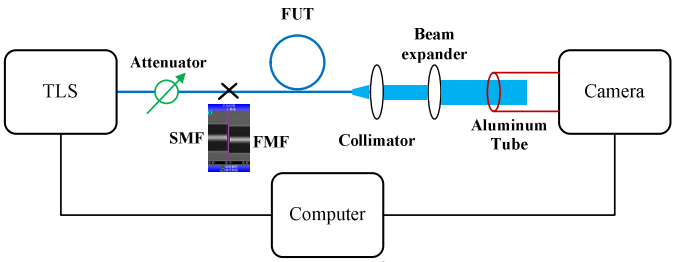


Fig.1 Schematic of the modified $S^2$ imaging system set-up.

Fig.1 showed the schematic of the modified $S^2$ imaging system set-up. The system was designed based on the combination of tunable laser source (TLS) and IR camera so as to allow for longer measurement fiber length and less measurement time. The 100 m length FUT was manufactured by OFS Corporation and the provided DMGDs between HOMs and FM were 2.0 ps/m ($LP_{11}$-$LP_{01}$), 3.0 ps/m ($LP_{02}$-$LP_{01}$), 3.9 ps/m ($LP_{21}$-$LP_{01}$). The collimator is used to transform the Gaussian beam to parallel beam. The expanding ratio of beam expander is 2.5. It is worth noting that an Aluminum tube was fixed on the front of camera to mitigate the EMI.

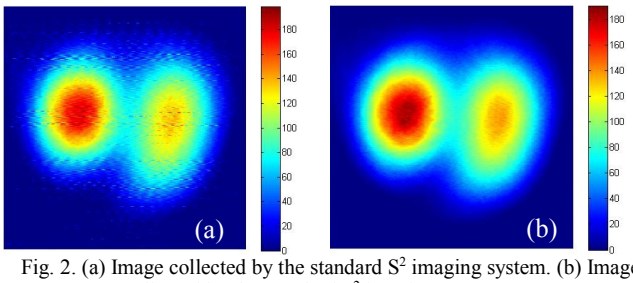


Fig. 2. (a) Image collected by the standard $S^2$ imaging system. (b) Image collected by the standard $S^2$ imaging system.

## III. RESULTS AND COMPARISON

The tunable laser was tuned from 193.415 THz to 193.926 THz with 0.001THz step size and the camera meanwhile recorded the modal picture under every frequency. With subsequent data processing, the plot of beat amplitude vs. DMGD and the calculated intensity distribution of modes can be obtained, which were shown in Fig. 3. Fig. 3 (a) was the result of modified $S^2$ imaging system while Fig. 3 (b) was the result of standard $S^2$ imaging system. It can be seen that the EMI has drastic influence to the measurement results.

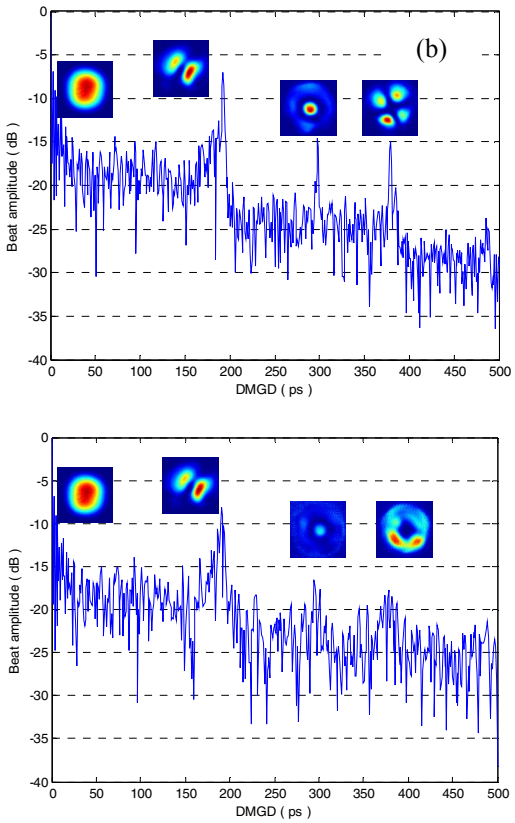


Fig. 3: (a) Measurement results of modified $S^2$ imaging system and (b) standard $S^2$ imaging system.

In the plot of beat amplitude vs. DMGD in Fig.3 (a), sharp spikes represent three HOMs, which are all discretely coupled from FM at the input of FTU. This process is referred to as discrete mode coupling. Alternatively, mode coupling occurred along the length of FUT is called distributed mode coupling, which appears as the long plateau between DMGD = 0 ps and 389.7 ps in the plot. MPI is defined as the ratio of powers in different modes. The total discrete mode coupling MPI and total distributed mode coupling MPI can be calculated by the following equations [7].

$$MPI_{discrete} = 10\log_{10}\left[\frac{\sum_{mn}\iint I_{mn}(x,y)dxdy}{\iint I_{01}(x,y)dxdy}\right] \quad (2)$$

$$MPI_{distributed} = 10\log_{10}\left[\frac{\iint I_{Fullband}(x,y)dxdy - \sum_{mn}\iint I_{mn}(x,y)dxdy}{\iint I_{01}(x,y)dxdy}\right] \quad (3)$$

Total distributed mode coupling was achieved by integrating the HOMs in the sharp peaks. By integrating the total HOM content of full band, and subtracting off the amount of power obtained from discrete mode coupling peaks, we obtained the total distributed mode coupling MPI.

Table.1 showed the comparison of total discrete and distributed mode coupling MPI measured by standard $S^2$ imaging system and modified $S^2$ imaging system. We can observe that the modified $S^2$ imaging system can improve the measurement accuracy of total discrete and distributed mode coupling by 1.41 dB and 2.67 dB.

Table 1. Comparison of total discrete and distributed mode coupling MPI measured by standard $S^2$ system and modified $S^2$ system

| | Standard | modified | Improvement |
|---|---|---|---|
| Total discrete mode coupling (dB) | -10.21 | -11.53 | 1.32 |
| Total distributed mode coupling (dB) | -14.44 | -15.66 | 1.22 |

## IV. CONCLUSION

In this paper, we utilized a modified $S^2$ imaging system for EMI shielding to achieve accurate measurement of mode coupling in FMFs. The total discrete and distributed mode coupling were obtained by standard and modified $S^2$ imaging system. The results showed that accurate measurement of mode coupling was achieved and the measurement accuracy of total discrete and distributed mode coupling were improved by 1.41dB and 2.67dB, respectively.


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