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Characterization of few mode fiber components and connected systems

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Abstract: Methods for measurement of polarization dependent loss and cross talk of individual few mode fiber components and connected systems are presented. A new method for determining the cross talk of the individual components, from the measurements on the connected system is presented and verified through simulations and measurements. The method is based on Fourier analysis of the wavelength dependent interference of the loss of the system.

1. Introduction

Few mode fibers and devices are currently actively researched for use in mode division multiplexing as a mean to increase the fiber capacity. Proper characterization of few mode fibers and components is important. The coherent swept wavelength interferometric method [1], has been reported as a method, which can measure the full transfer matrix including phase and polarization of a connected few mode system. However, this method requires a complicated coherent detection setup and the complex transfer matrix might not always be easy to interpret.

In this paper, a new and more simple technique is proposed based on polarization dependent loss measurements of the connected system. It is shown that by analyzing the measurement of a connected few mode system, it is possible to calculate the crosstalk of the individual components. This is for example very useful for a setup for a transmission experiment to identify the origins of cross talk. It is especially useful for characterization of the final splice, which cannot be characterized otherwise.

The proposed method is general but, as an example, the focus is on the system shown in Fig. 1 consisting of two connected photonic lanterns.

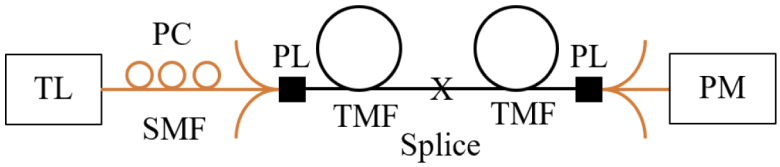

Fig. 1. Setup for characterization. TL: Tunable Laser, PC: Polarization Controller, PL: Photonic Lantern, SMF: Single Mode Fiber, TMF: Two Mode Fiber, PM: Power meter.

2. Measurements

The photonic lanterns characterized are mode selective three fiber lanterns for multiplexing and demultiplexing of a two mode fiber (TMF) [2]. The lanterns consist of three fibers fused together, down tapered, and spliced to the TMF. After down tapering, the surrounding air acts as the low index cladding. The taper is made using one standard single mode fiber (SSMF) and two Corning HI1060 (HI) single mode fibers. The SSMF is for coupling to the fundamental mode of the TMF

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and the two HI fibers are for coupling to the LP_{11a} and LP_{11b} mode group. The TMF is an OFS step index TMF [3].

Before measuring on the connected lantern system of Fig. 1, the individual lanterns (including a short length of TMF) are characterized with respect to polarization dependent loss, and crosstalk. Previous work [2] shows that both loss and cross talk of photonic lanterns depend on the input polarization. Three sets of measurements are taken for each lantern: multiplexing loss, multiplexing cross talk, and demultiplexing loss. In the multiplexing loss measurements, the loss from each of the three input fibers to the output TMF is measured. The multiplexing cross talk is measured using spectral and spatial resolved imaging (S^2 imaging) [4]. Ten S^2 measurements are taken where the polarization is randomly varied between each measurement. For the demultiplexing loss, the loss is measured from the TMF to each of the three lantern-output-fibers for both LP_{01} and LP_{11} into the TMF. For the LP_{01} launch into the TMF, a splice to SSMF followed by a mode stripper is used. For the LP_{11} launch into the TMF, a thermally induced long period grating [5] is used with a conversion efficiency > 99.5 % for all input polarizations in the considered wavelength range. The insertion loss of the long period grating, including splice to input single mode fiber, is 0.4 dB with a PDL of less than 0.06 dB [5]. That is, the polarization dependency of the long period gratings are much less than that of the lanterns and can therefore be ignored.

For the loss measurements, the tunable laser is scanned in a wavelength range and with a step size appropriate to resolve the interference due to the beating between the modes. The wavelength beat period λ_B can be found from the differential group delay (DGD) of the TMF as [6]:

$$\lambda_B = \frac{\lambda^2}{DGD \cdot c}, \tag{1}$$

where λ is the wavelength, and c is the speed of light in vacuum. The TMF used has a DGD per unit length of 2.1 ps/m and the TMF length was in the range of 2 to 5 m, so a wavelength range of 1545 to 1555 nm and a step size of 0.1 nm were used. Ten wavelength scans are taken where the input polarization is fixed during the scan but randomly varied between each scan. Furthermore, a polarization dependent loss (PDL) measurement is done for the same wavelength range and step size using the polarization scanning method [7]. Here, for each wavelength step, the output power is monitored while the polarization controllers are varied randomly for a time long enough to assure that the entire Poincare sphere is covered. The maximum and minimum output power is recorded for each wavelength step.

An example of a demultiplexing loss measurement on the output lantern is shown in Fig. 2. This measurement is from LP_{11} launch into the TMF to the sum of powers out of the two HI output fibers, thereby measuring the total LP_{11} power. As it should be expected, it is observed that the fixed polarization measurements lie within the PDL range. The fast oscillations results from the interference between the modes. On top of that the polarization dependence is observed, which, in this case, is higher than just the variation due to interference. The strong polarization sensitivity for the LP_{11} input is due to the rotation of LP_{11} with polarization [6] and the resulting change in mode overlap in the lantern.

For the connected lantern system of Fig. 1, the loss is measured from each of the three inputs to the SSMF output as well as to the sum of powers out of the two HI outputs. As for the measurements on the individual lanterns, the loss is measured for 10 randomly chosen fixed inputs polarization and furthermore, a PDL measurement is taken. As an example, the result from a HI input of the first lantern to the sum of powers out of the two HI outputs of the second lantern is shown in Fig. 3. In this case, unlike the measurements of Fig. 2, it is observed that the interference dominates over the polarization dependency.

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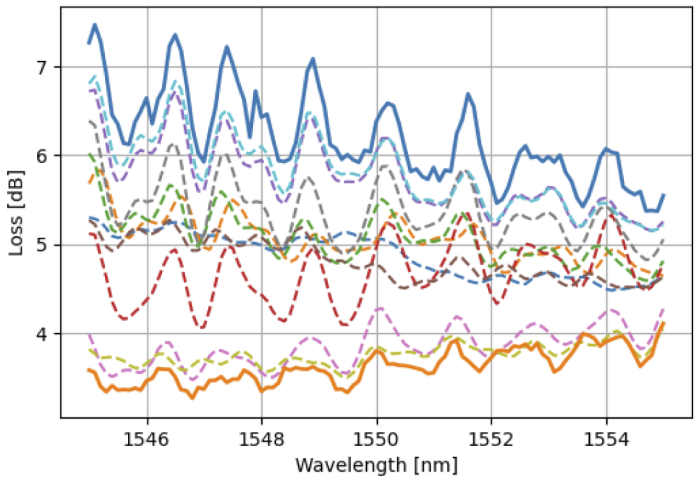

Fig. 2. Example of demultiplexing loss measurement from LP_{11} input to the sum of powers out of the two HI fibers. PDL max and min are shown by continuous lines, and 10 measurements with arbitrary fixed polarization by dotted lines.

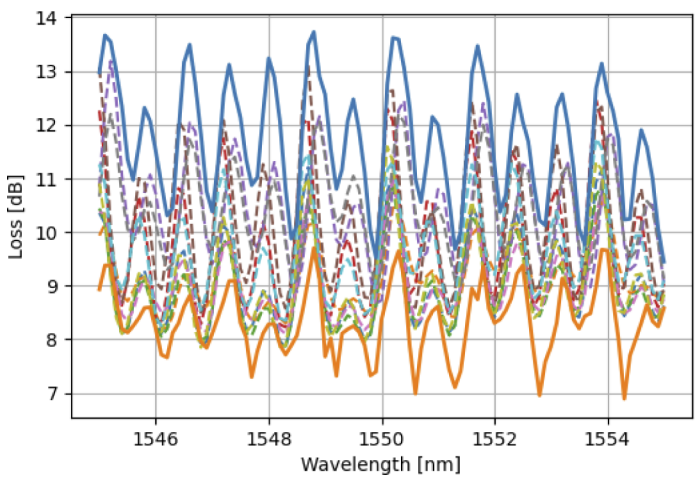

Fig. 3. Measurement result for two connected lanterns (Fig. 1). Loss from HI input to sum of HI outputs. PDL max and min are shown by continuous lines, and 10 measurements with arbitrary fixed polarization by dotted lines.

3. Analysis

To evaluate the interference beating, a Fourier transform is taken of each of the ten fixed polarization loss measurements of Fig. 3. The result is shown in Fig. 4. The peak to peak beat amplitude is shown as a function of differential group delay (*DGD*) using (1). The length L_1 from the input lantern to the splice is 2.25 m, and the length from the splice to the output lantern (L_2) is 3.05 m. Further, using that the TMF *DGD* per unit length is 2.1 ps/m, it is seen that the main peak at 11 ps corresponds to the beating between the input and output lanterns, the peak at 4.8 ps corresponds to the beating between the input lantern and the splice, and the peak at 6.3 ps to the beating between the splice and the output lantern. From the Fourier transforms, it is also observed how the beat amplitude changes versus input polarization, due to the polarization dependency of the cross talk in the multiplexers and splice.

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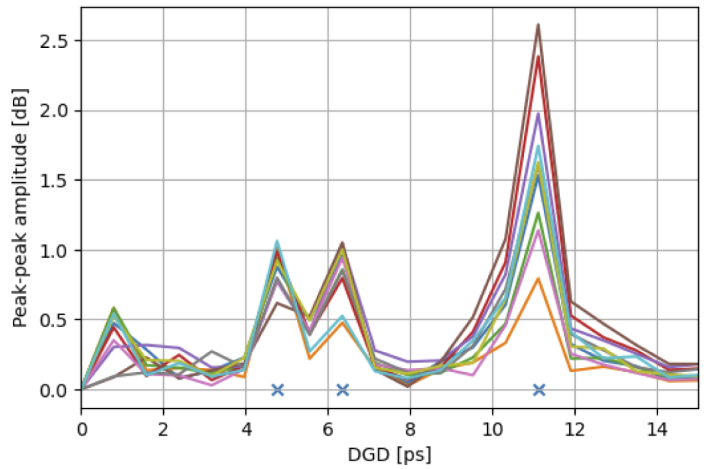

Fig. 4. Fourier transforms of the 10 fixed polarization measurements of Fig. 3.

From the peak to peak amplitude of the beating ΔP^{dB}, the ratio between power in the parasitic mode P_P and the power in the dominant mode P_D can be found [6,8]:

$$R = \frac{P_P}{P_D} = \left(\frac{10^{\frac{\Delta P^{dB}}{20}} - 1}{10^{\frac{\Delta P^{dB}}{20}} + 1} \right)^2 . \tag{2}$$

This ratio is calculated for each of the three peaks corresponding to the lengths L_1, L_2, and $L_1 + L_2$ and labeled R_{L1}, R_{L2}, and R_{L1+L2}.

In the following, it will be shown how these three ratios R_{L1}, R_{L2}, and R_{L1+L2} are related to the parameters of the components of the system. The system of Fig. 1 can (ignoring splice loss) be modelled as shown in Fig. 5, where the dominant mode is either LP_{01} or LP_{11} depending on the considered in- and output fibers of the lanterns. α_{in} is the attenuation coefficient in linear unit of the input lantern, α_{outD} and α_{outP} are the attenuation coefficients of the output lantern for dominant mode in and parasitic mode in respectively. R_{in} is the ratio between the parasitic power and the dominant power out of the input lantern. R_{spD} is the ratio between the parasitic power and the dominant power out of the splice for dominant mode into the splice. Similar, R_{spP} is the ratio between the dominant power and the parasitic power out of the splice for parasitic mode into the splice. For the interference over the length L_1 there are two interference path A, B to C, and A, B to D. However, the power, which reach the output will be dominated by the path A, B to C. Therefore, R_{L1} is related to the component parameters R_{in} and R_{spP} as:

$$R_{L1} \approx \frac{\frac{R_{in}}{1+R_{in}} \frac{R_{spP}}{1+R_{spP}}}{\frac{1}{1+R_{in}} \frac{1}{1+R_{spD}}} \approx R_{in} R_{spP}, \tag{3}$$

where R_{in}, R_{spD}, and R_{spP} are all assumed to be $\ll 1$. Similarly, it is found:

$$R_{L2} \approx R_{spD} R_{out}. \tag{4}$$

$$R_{L1+L2} \approx R_{in} R_{out}. \tag{5}$$

where $R_{out} = \frac{\alpha_{outD}}{\alpha_{outP}}$.

It will now be further assumed that $R_{spD} = R_{spP}$ (and labeled R_{sp}), which is a good approximation, when it is the same type of TMF, which is spliced together. Then, it is possible to find the cross

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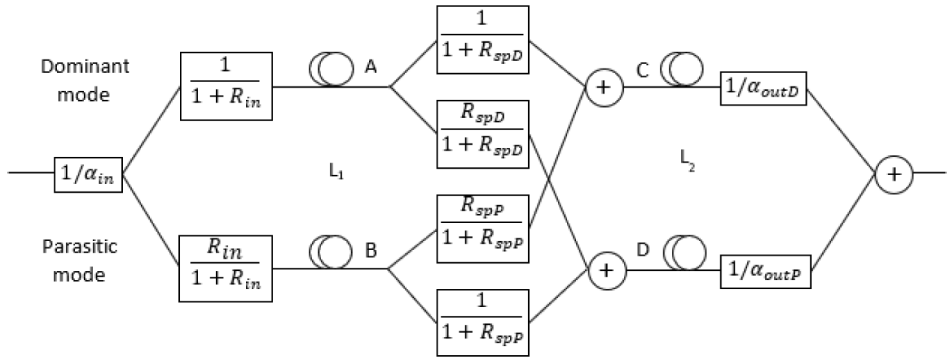

Fig. 5. Model of the system of Fig. 1.

talk ratios for the individual components from R_{L1}, R_{L2}, and R_{L1+L2} found from the measurement of the connected system:

$$R_{sp} = \sqrt{\frac{R_{L1}R_{L2}}{R_{L1+L2}}}. \tag{6}$$

$$R_{in} = \sqrt{\frac{R_{L1}R_{L1+L2}}{R_{L2}}}. \tag{7}$$

$$R_{out} = \sqrt{\frac{R_{L2}R_{L1+L2}}{R_{L1}}}. \tag{8}$$

4. Results

To verify the method, the system of Fig. 1 has been simulated using a linear propagation model [9] and using parameters close to actual measured values on real lanterns and splices. Loss versus wavelength has been modeled from input to output and Fourier transformed. The ratios R_{L1}, R_{L2}, and R_{L1+L2} are then calculated using Eq. (2), and finally, the parasitic to dominant mode power ratios for the splice, input and output lantern are calculated using Eq. (6) to (8). Simulation results for the the parasitic to dominant mode power ratios estimated from the simulated beat amplitudes compared with the, in the model, actually used component values are shown in Table 1. Results are shown both for SSMF input to SSMF output (the LP_{01} channel) as well as for HI input and output ports (the LP_{11} channel). A good agreement within about a dB is observed. Further simulations have been performed, where the parasitic to dominant power ratios for the various components have been swept between −8 and −20 dB. The agreement between actual and estimated cross talk ratio are still typically within 1-2 dB.

Table 1. Simulation results for parasitic mode to dominant mode power ratios estimated from beat amplitudes compared to actual values used in the model for SSMF input to SSMF output and HI input to HI output.

	SSMF to SSMF		HI to HI	
	Actual dB	Estimated dB	Actual dB	Estimated dB
Splice	−16.9	−18.1	−16.9	−17.9
Input lantern	−10.6	−9.8	−13.8	−12.5
Output lantern	−9.0	−10.0	−6.0	−7.4

For the experimental verification, the connected lanterns has been analyzed using measurements for all three inputs in both direction, six measurements in total. One of the (two) results for SSMF

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input to SSMF output (the LP_{01} channel) is as an example summarized in Table 2. The parasitic to dominant mode power ratios estimated from measurement on the connected lanterns using the method of Sec. 3 are shown. For comparison, the actual measured values on the individual lanterns using the measurement methods of Sec. 2 are shown. Average and standard deviation for the measurement on 10 different input polarizations are shown. For the input lantern, the parasitic to dominant mode ratios are from the ten S^2 measurements. For the output lantern, the measured ratio is the ratio of the loss from LP_{11} input to SSMF output over the loss from LP_{01} input to SSMF output. The average of the 10 individual measurements is used to calculate the average ratio and the standard deviation is root of the square sum of the standard deviation for the two loss measurements. The individual component measurement for the splice is a typical measurement result from an S^2 measurement on a splice alone.

Table 2. Parasitic mode to dominant mode power ratios estimated from measurements on the connected system compared to actual measured values on the individual components for SSMF input to SSMF output (the LP_{01} channel). Average and standard deviation from measurement on 10 different input polarizations are shown.

	Estimated from measurement on connected system		Individual component measurement	
	Average dB	Stand. dev. dB	Average dB	Stand. dev. dB
Splice	−18.7	2.2	*−20*	*1.5*
Input lantern	−10.9	4.0	−14.9	3.5
Output lantern	−12.6	6.5	−10.4	2.2

A reasonable agreement between estimates from the Fourier analysis on the connected lanterns and the measurements on the individual components is observed. A general observation when including the five not shown measurements is that the sum of the cross talk of the input and output lantern is estimated reasonably well within a few dB, while the cross talk of the individual lanterns is harder to estimate.

5. Conclusion

A simple method for measurement of polarization dependent loss and cross talk for individual few mode fiber components as well as a connected few mode fiber system is presented. The polarization dependency is analyzed by measuring loss for different fixed input polarization and compared to a full PDL measurement using the polarization scanning method. It is observed that in some cases, the loss varies mostly due to interference, while in other cases, it varies due to polarization dependency.

A proposed new method based on Fourier analysis of the wavelength dependent interference for a connected few mode system can estimate the cross talk of the individual components. The new method has been verified using both simulations and measurements.

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Disclosures. The authors declare no conflicts of interest.

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