Modal Analysis of Fiber-optical Devices using Digital Holography

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Abstract: Digital holography is a device characterization technique that provides the full optical field, both phase and amplitude, as a function of input port and polarization. Further offline digital signal processing of these fields can provide meaningful insight in to the device-under-test. Here, digital holography is used to characterize a polarization-dependent loss emulation stage and a three-mode photonic lantern. Digital demultiplexing yields the full polarization-diverse transfer matrix from which important metrics such as mode-dependent loss and cross-talk deduced.

1. Introduction

In recent years, space-division multiplexing (SDM) has emerged as a promising candidate to further extend the capacity of optical fiber beyond what is possible with single-mode technology. With the advent of spatially diverse optical fibers such as few-mode, multi-mode, multi-core, coupled-core, and few-mode multi-core fibers, and multiplexer devices for those fibers, for example photonic lanterns (PLs) [1], came the desire for proper characterization of thereof. Performance metrics such as mode-dependent loss (MDL) could be obtained at a system-level through analysis of the taps [2] of the multiple-input multiple-output (MIMO) equalizer required to unravel the mixing of the spatial paths in SDM transmission. Optical vector network analyzers (OVNAs) [2, 3] were developed to better characterize (SDM) fiber-optic components by providing the full polarization-diverse transfer matrix, analysis of which reveals meaningful performance metrics such as cross-talk (XT) and MDL. However, since the components required for the OVNA are all in single-mode domain, a multiplexer-demultiplexer pair is required and characterization of a single multiplexer is not possible since there is no access to the (non-single-mode) SDM domain. Note that some advances for measuring single multiplexers with OVNA using a reflective measurement setup were made [3].

In this work, digital holography is introduced as a characterization technique capable of measuring the full polarization-diverse complex field of a device of interest. Since the technique provides access to the intermediary SDM domain, e.g. few-mode or multi-mode, a single multiplexer device can be characterized on it own as opposed to a multiplexer-demultiplexer pair. Digital demultiplexing of the measured fields provides a transfer matrix, from which quantitative performance metrics such as MDL and XT can be calculated. A polarization-dependent loss (PDL) emulation stage is characterized to prove the principle of PDL analysis using digital holography. Furthermore, a three-mode PL is characterized and is shown to have an MDL of 2.2 dB and −13.1 dB XT at 1550 nm.

2. Digital Holography

Off-axis digital holography [4–6] is a technique capable of measuring the full polarization-diverse complex field emitted from a device-under-test (DUT). The light emitting surface, in this case the facet of a fiber, is placed in a 4f optical setup as shown in Fig. 1. Note that the distances between the lenses in Fig. 1 are not drawn to scale to conserve space. The optical setup combines the light emitted from the facet, the *signal*, with a coherent flat-phase reference beam and images it magnified to the ratio of the lenses on the surface of the infrared camera. A Wollaston prism is used to spatially split both polarizations. The reference beam is placed under a slight angle, hence *off-axis* digital holography, which leads to fringes produced by the beating between the reference beam and the signal. Even though the camera only records the intensity of incident light and would thus destroy any phase information, it is still preserved in the fringe pattern and can therefore be extracted by subsequent digital signal processing (DSP).

The DSP chain for digital holography starts with masking or cropping of a region of interest of the recorded camera frame as shown in the insets of Fig. 1. The Fourier transform is used to convert this region from the spatial domain, *real-space*, to the angular domain, *k-space*. The intensity recorded by the camera

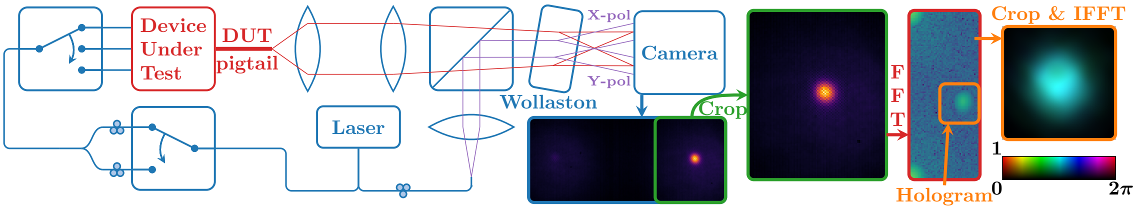
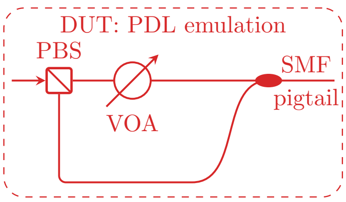


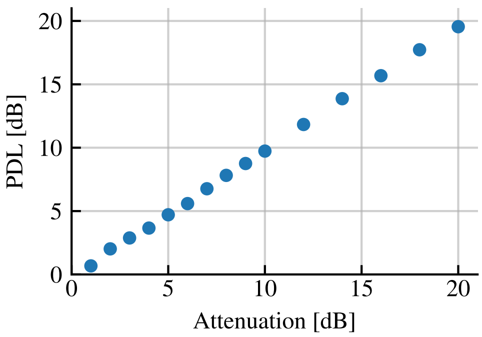
Figure 1: Digital holography setup for a generic device-under-test (DUT). Beating of light from the DUT and light from the reference arm creates a fringe pattern, images of which are recorded for every input and polarization. Hologram extraction is performed through cropping of the interference pattern per polarization, a Fourier transform, cropping of the hologram, and an inverse Fourier transform. The extracted hologram is a complex field from which a 2Nx2N polarization-diverse transfer matrix can be derived.

can be described by $|s+r|^2 = |s|^2 + |r|^2 + sr^* + s^*r$. Since signal and reference are placed under an angle, the beating between them, described by sr^* and s^*r, appears at an angle as well, whereas the square terms $|s|^2$ and $|r|^2$ end up at DC. This allows for the extraction of the desired sr^* term through masking or cropping. An inverse Fourier transform is used convert to real-space where now the full complex, i.e. both amplitude and phase, scaled image of the facet of the DUT is at our disposal. If the measurement apparatus is calibrated and aligned perfectly, this field can be used for subsequent processing. However, residual phase errors will be present in the extracted field if the measurement apparatus is not perfectly aligned. For example, tilt of the camera can lead to linear phase errors as shown in Fig. 2d for the field emitted from a single-mode pigtail. If the DUT or reference is not perfectly in the focal point, this can lead to a quadratic phase front as shown in Fig. 2f. Luckily, these linear and quadratic phase errors can be estimated and subsequently removed, revealing the correctly extracted field as shown in Fig. 2c.

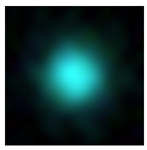
The phase-corrected extracted fields are considered the end result of the digital holography since the full polarization-diverse complex field present at the facet of the DUT is known. However, these fields can be used for further processing and analysis, one particularly interesting use is the construction of a transfer matrix through *digital demultiplexing*. A suitable modal basis is chosen, in this case a Gaussian spot with appropriate beam width, and the overlap integral with the extracted field is calculated. Since this overlap is calculated digitally and the modal basis can be chosen freely, for example the mode profile of an optical fiber or device of interest, this technique is called *digital demultiplexing*. These overlaps reveal one column of the transfer matrix since the extracted field is the measured output of one particular input port and polarization of the DUT. The full transfer matrix is obtained when the measurement is repeated for each input port and polarization. Since the extracted fields are discretized, the overlap integral is replaced by a double sum and each transfer matrix element, one for every input and mode combination for both polarizations, is calculated



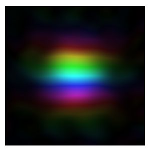
(a) PDL emulation stage which is placed as DUT in the measurement setup of Fig. 1



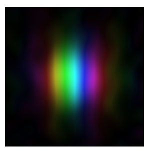
(b) Measured PDL using (a) and Fig. 1



(c) Correct



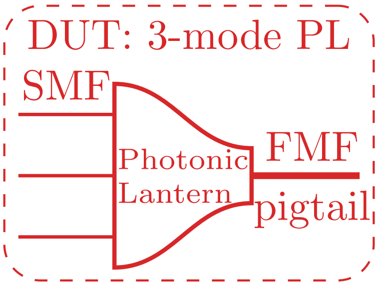
(d) Linear in Y



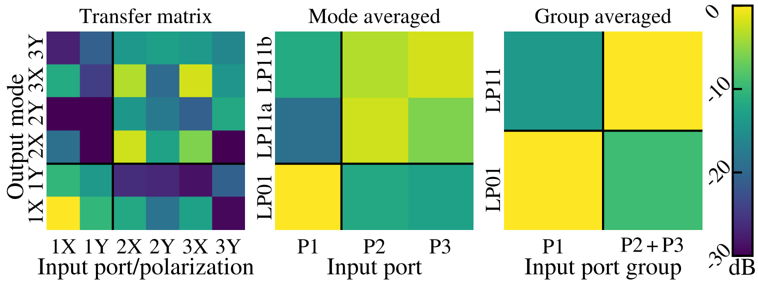
(e) Linear in X

(f) Quadratic

Figure 2: (b) shows the polarization-dependent loss (PDL) measured with the digital holography setup of Fig. 1 with (a) as DUT. Good agreement between the measured and artificially introduced PDL is observed. (c) shows the measured output field profile of the single-mode pigtail of (a) when all phase corrections are performed. (d), (e), and (f) show the output field profile when residual phase errors are present.



(a) DUT placed in setup Fig. 1



(b) Measured transfer matrices of (a): per polarization, mode, and mode-group

Figure 3: (b) shows the transfer matrices of a 3-mode PL measured using the setup of Fig. 1 with (a) as DUT. The full 6x6 transfer matrix is calculated using an overlap integral between the measured complex fields shown in Fig. 4 and reference graded-index mode profiles. Mode and mode-group transfer matrices are derived by averaging the full matrix, revealing a mode-group crosstalk of −13.1 dB and a MDL of 2.2 dB at 1550 nm. Black lines in the transfer matrices divide the mode-groups.

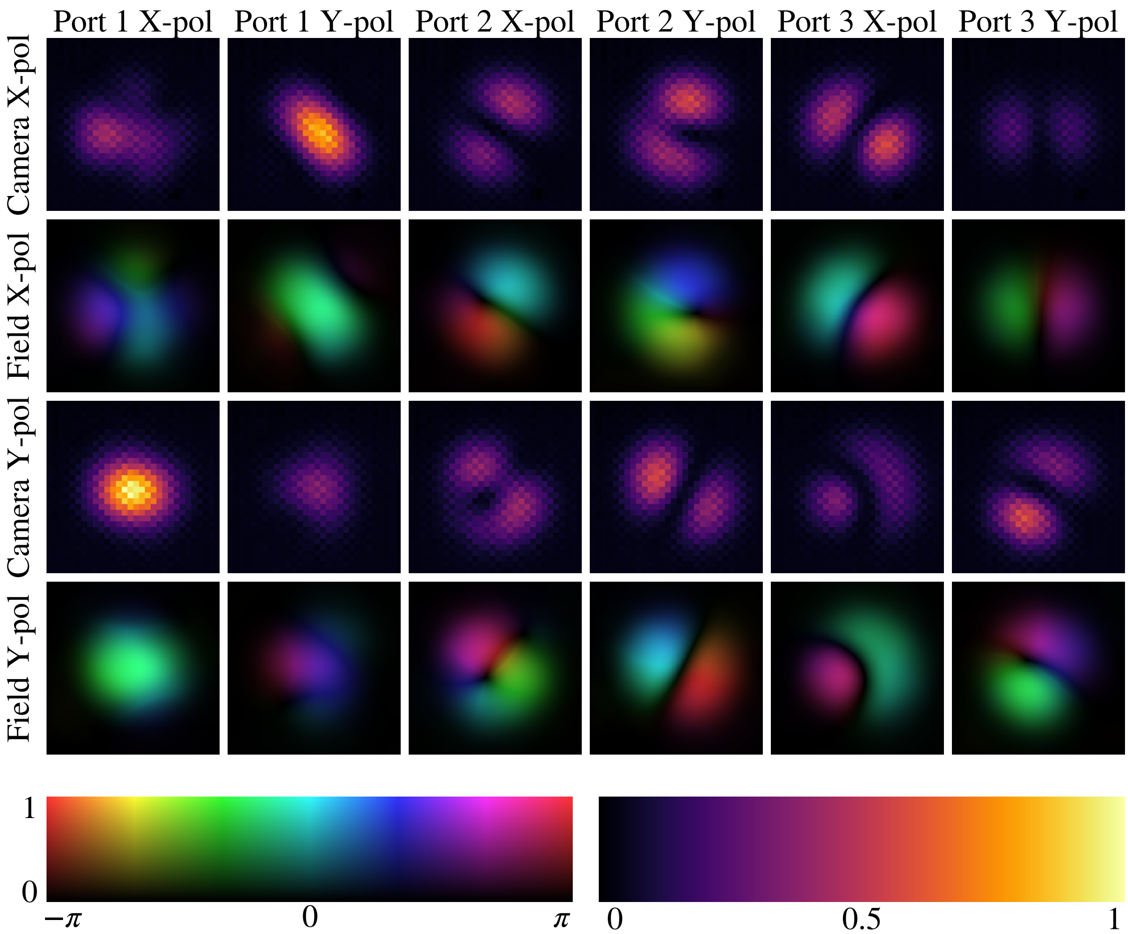


Figure 4: Measured camera images and extracted complex fields for every input, input polarization, and output polarization combination of the 3-mode PL measured using the setup depicted in Fig. 1 with Fig. 3a as DUT. Note that the camera only records the intensity of the fringe patterns, and that the extracted complex fields contain both amplitude and phase information. Mode selectivity is observed: port 1 mainly excites the LP_{01} mode, whilst port 2 and 3 mainly excite the LP_{11} modes. The extracted fields can be used to calculate the transfer matrix depicted in Fig. 3b.

as follows [6]:

$$\boldsymbol{T}_{i,j} = \sum_y \sum_x \boldsymbol{M}_i(x,y) \cdot \boldsymbol{\Phi}_j^*(x,y) \quad \text{for } i,j \text{ in } \{1,2,...,2N\} \tag{1}$$

where $\boldsymbol{M}_i$ are the phase-corrected extracted fields, $\boldsymbol{\Phi}_j$ the chosen reference modes, and N the number of modes. Interesting metrics such as insertion loss (IL), XT, and PDL or MDL can be directly calculated from this transfer matrix. Fig. 2a shows a PDL emulation setup where the polarizations are split, one is attenuated using a variable optical attenuator (VOA), both are recombined, and fed in to a single-mode pigtail which is measured using the digital holography setup depicted in Fig. 1. PDL is calculated through singular value decomposition (SVD) of the transfer matrix and plotted in Fig. 2b. A clear linear dependence between the emulated and measured PDL is observed, proving the principle of measuring PDL using digital holography.

3. Analysis of a 3-Mode Photonic Lantern

A three-mode mode-selective PL [1] with a graded-index few-mode fiber (FMF), see Fig. 3a, is measured using the digital holography setup of Fig. 1. The characterization is performed for each input and polarization at 1550 nm. The captured camera images and extracted fields are depicted in Fig. 4. Note that the camera only captures the intensity of the fringes, i.e. $|s+r|^2$, while the extracted fields contain both amplitude and phase information, i.e. sr^*, with the appropriate phase corrections as explained in the previous section. Mode selectivity can already be observed from the raw camera images as port 1 mainly excites the Gaussian-like LP_{01} mode, whereas ports 2 and 3 produce a pattern in which the side-lobes of the LP_{11} modes can be seen. Quantitative information, however, such as XT and MDL, cannot be inferred from these raw camera images. Digital demultiplexing of the extracted fields yields the transfer matrix shown in Fig. 3b, which is then summed and averaged to obtain metrics per mode and per group. XT and MDL can be derived from the group-averaged and full transfer matrix, respectively [6]:

$$XT = \frac{tr(\hat{\boldsymbol{T}})}{\sum \hat{\boldsymbol{T}} - tr(\hat{\boldsymbol{T}})}, \quad MDL = \frac{\lambda_1^2}{\lambda_{2N}^2} \tag{2}$$

where $\hat{\boldsymbol{T}}$ denotes the group-averaged transfer matrix, $tr(\cdot)$ the trace operator, λ_1 the strongest singular value of the full transfer matrix $\boldsymbol{T}$, and λ_{2N} the weakest. For this PL, MDL is measured to be 2.2 dB at 1550 nm, while XT is −13.1 dB, confirming mode(group)-selectivity.

4. Conclusion

The principle behind digital holography and the optical setup and digital signal processing required to use it for fiber-optical component characterization are introduced and explained. As a proof-of-principle, digital holography is successfully used to obtain polarization-dependent loss (PDL) artificially introduced by a PDL emulation stage. A major advantage of digital holography over other measurement techniques is digital demultiplexing, which allows for the characterization of a single multiplexer device as opposed to a pair. A single three-mode photonic lantern (PL) is characterized, yielding the amplitude and phase of the field emitted from the device for each input port and polarization. Further analysis provides the full polarization-diverse complex transfer matrix used to calculate quantitative performance metrics which cannot be inferred from raw camera images. The mode-selectivity, qualitatively observed from the raw camera images, is quantified by cross-talk which is calculated to be −13.1 dB at 1550 nm. Mode-dependent loss, which cannot even be evaluated qualitatively, is measured to be 2.2 dB. Additional measurements at other wavelengths need to be carried out at a later stage to evaluate the broad-band operation of the PL.

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