Stability of coherent signal transport in few mode fibres.

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At ASTRON research is done on technology for radio astronomical antenna arrays with diameters exceeding 100 m. One of the potential methods of beamforming is based on coherent optical processing of signals transported by optical fibre. This raises questions about stability of differential optical phase and polarization. Singlemode telecom fibres in a 48 strand cable have been tested with a Young interferometer operated at a wavelength of 633 nm. Then the fibres are neither single nor multi moded, which complicates the theoretical interpretation. We describe our setup and experimental results taken in realistic operating conditions. We conclude that adaptive coherent processing will be possible provided that the effective integration time is less than 100 ms.

Introduction

Astron is involved in an international project called the Square Kilometre Array. The object of this project is to build a radio telescope with an effective receiving surface of one square kilometer with an receiving range between 0.03 and 20 GHz. Astron has chosen to achieve this by the use of adaptive antenna arrays, placed in order hundred of stations with a diameter of up to 300 m.[1] This means beamforming has to be done at a high bandwidth on about 10^3 elements per station array. A promising option to do this is photonic beamforming, given the fact that the high bandwidth signal needs to be transported via optical fibres. Especially coherent optical beamforming techniques based on photorefractive media like BEAMTAP [2] can easily handle such large numbers of elements. However such coherent processing requires phase stability at optical wavelength. This converts to differential optical path length fluctuations less than 100 nm over typical coherent processing adaption times of order 100 ms. A 100 nm differential length change between two fibres of 100 m is already induced by a temperature difference of 1 mK [3]. The second source of length fluctuation is caused by mechanical deformations, such as could be induced by acoustical waves.

Since the BEAMTAP method allows singlemode as well as multimode fibre input, we decided to use standard 9/125 μm fibre for cost reason. For light at 633 nm we are then in a few mode regime with a polarization behaviour for which not very much is known.

For the feasibility of this application, three stabilities are relevant and examined experimentally: The fringestability, the polarization stability and the mode stability. Because our interrest is primairly in the application of a system like this in the field, it is tried to keep the experimental environment as close as possible to the practical system needed. For that reason we used a standard 6x8 telecomcable to get the proper stress environment.

Results from previous work

Coherent optical processing techniques work with wavelengths between 532 nm and 1064 nm. We choose to work at 633 nm for ease, using equipment that is widely available. The first experiments started with 4/125 μm fibre and unpolarized light of a HeNe-laser, which is singlemode for 633 nm. The length of the fibres in this experiments varied from 1 to 10 m[4]. The experiments were taken a step further by A. Sportel[5], who used 9/125 μm and extended the length of the arms in the interferometer to 100 m.

Measurement method

The measurement configuration shown in fig 1, uses a Young interferometer to generate a fringepattern by free space interference of the light beams, emerging from two single moded 4/125 μm fibres with 175 μm separation. The fringe pattern moves if the phase between the two beams changes and is recorded by a CCD camera. The light of the HeNe-laser is linearly polarized and focussed on a single moded 4/125 μm fibre. Then it is splitted into a path to the interferometer and a path that produces a spot of reference intensity on the CCD. The interferometer is fed by a SM splitter, but the fibres under test can have a core diameter larger than 4 μm. Before the pattern is imaged on the CCD camera, a polarization analyzer can be rotated, to determine the polarization angle. An example of a 20 ms cameraframe can be seen in figure 2(a)

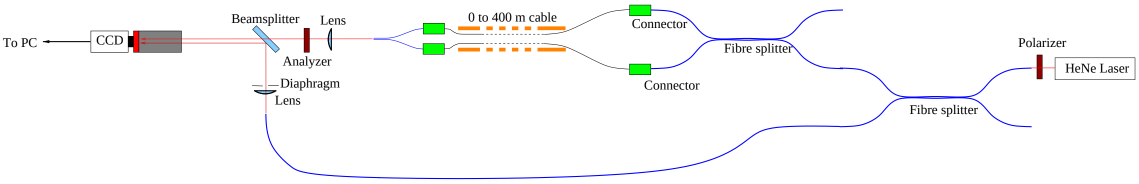


Figure 1: The measurement configuration

In the used measurement method five movies of 5 seconds each are recorded with a framerate of 10 fps. The movies have information on the following: fringecontrast, background light, intensity of an arm, the maximum and minimum intensity of an arm. All corresponding polarization angles are also measured. One measurement takes several minutes, and to determine stability several measurements are compared with each other as well as the frames in a movie.

Three types of analysis are done on a measurement. First, the correlation between the frames within an measurement movie is calculated to find the shift of the fringepattern. In equation (1) is R the correlation coëfficient, A the intensity in first frame, B the intensity of the current frame, M the total number of lines, N the total number of columns (for processing reasons, not the whole frame is used for the calculation) i the current line and j current column.

$$R = \frac{1}{M}\sum_{i=1}^{M}\left(\frac{\sum_{j=1}^{N}\left(\left(A_{ij}-\frac{1}{N}\sum_{j=1}^{N}A_{ij}\right)\left(B_{ij}-\frac{1}{N}\sum_{j=1}^{N}B_{ij}\right)\right)}{\sqrt{\sum_{j=1}^{N}\left(\left(A_{ij}-A_i\right)^2\right)*\sum_{j=1}^{N}\left(\left(B_{ij}-B_i\right)^2\right)}}\right) \tag{1}$$

As long as as the phaseshift between successive frames is less than 180^{o}, we can derive the direction of the change unambiguously. Faster changes lead to reduced fringe contrast, which is verified. A change in phaserate can be determined by analysis of the correlation between successive frames. When the phase between the two arms changes with constant rate then R is a cosine function of time.

Secondly, the fringecontrast(FC) is calculated [6] with the Michelson formula (2) for visibility corrected for background, I_b, which is calculated from the background light movie.

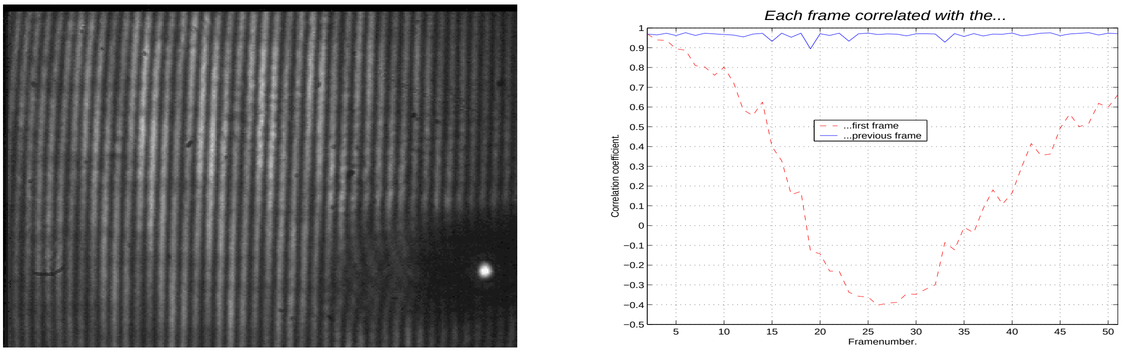
$$FC = \frac{I_x - I_n}{2\,(I_a - I_b)} \tag{2}$$

Here I_x is the maximum, I_n the minimum and I_a the average fringe intensity.

The last analysis done is on the measurements of the intensity. This depends on the effective light coupling from the few moded 9 μm core into the singlemode 4 μm core. This measurements are normalized to the intensity of the laser at the moment of the measurement. After this analysis intensities and angles can be compared between measurements.

Measurement results

An example of the results of the correlation can be seen in figure 2(b). The correlation with the first frame (dashed line) shows a cosine function of time. The correlation between the consecutive frames (continuous line) is a time derivative, i.e. a measure of the framespeed. While in all the measurements the correlation with the previous is a fairly straight line between 0.95 and 1, shows a part of a cosine which not reaches the value of -1 before turning. This means the fringerate changes direction. The results of all the analysis can be found in table 1. The first two parameters are an indication of the fringestability, the second two of the polarization stability and the last for the modestability. All stabilities are expressed in rates, i.e. a change per second, for fringefraction, fringecontrast, polarization angle, polarized fraction, and normalized intensity in a single fibre, so the closer to zero these rates are, the better the stability is.



(a) **(b)**

Figure 2: (a) an example of a cameraframe and an example of a correlation graph

Since we do a differential measurement we find positive and negative fringephaserates,

Table 1: Results of analysis.

	fringephaserate $[\mathrm{s}^{-1}]$	$\frac{\Delta FC}{\Delta t}$ $[\mathrm{s}^{-1}]$	$\frac{\Delta\phi}{\Delta t}$ $[\mathrm{deg}*\mathrm{s}^{-1}]$	$\frac{\Delta\frac{I_{\max}}{I_{\min}}}{\Delta t}$ $[\mathrm{s}^{-1}]$	$\frac{\Delta I_{norm}}{\Delta t}$ $[\mathrm{s}^{-1}]$
Laboratory	±35	$7*10^{-5}$	0.02	$2.5*10^{-3}$	$3*10^{-5}$
In ground	±60	$6*10^{-5}$	0.004	$2.4*10^{-4}$	0

uniformly distributed over the indicated range. The $\frac{\Delta\phi}{\Delta t}$ and the $\Delta\frac{I_{\max}}{I_{\min}}/\Delta t$ parameters, to determine the polarization stability are even order 5 and 10 better in the ground than in the laboratory. This could be related to the curvature of the fibres on the reel in the laboratory. The change in $\frac{\Delta I_{norm}}{\Delta t}$ is in the case of the measurements in the ground too small to determine, so this should be good enough to work with.

Conclusions

In this paper it is experimentally shown that a signal can be transported phase stable over few hundreds of metres. Three stabilities were examined: the fringestability, polarization stability and mode stability. These three parameters were tested in two environments.
The experiments with the fibre on a reel in the laboratory and with the fibrecable in the ground gave comparable, results. The polarization stability and the mode stability have longer timeconstants in the ground. With the achieved results, is should be possible to use coherent processing with an integration time less than 100 ms over this fibres. It turned out that the last pieces of the cable inside the buildings on both sides pick up most of the disturbances. In an application this disturbance could be cut down for a big part.
A final conclusion of this article can be drawn: Because of the good stability of normal fibre, optical coherent signal transport over distances up to 300 m are possible, and it should be able to use this for some kinds of optical coherent processing.

References

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