Phase-Locking of Tiled Fiber Array using SPGD Feedback Controller

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ABSTRACT

We present the laboratory experiments of phase locking of a multi-channel tiled fiber array using a stochastic parallel gradient descent (SPGD) feedback controller demonstrating the compensation effect of the simulating phase-induced distortions based on the model-free optimization of the received signal strength. An all-polarization-maintaining (PM)-fiber optical configuration is used to simplify the free-space transceiver system. The atmospheric aberrations are simulated by a multi-channel integrated optical phase modulator which obtains input control voltages from an array of multi-channel independent sinusoidal signal generators. A similar multi-channel phase modulator which obtains input control voltages from a computer-based SPGD controller is used to compensate the simulating phase distortions. The experimental results show that the constructive interference state is reached through phase locking of the multi-channel tiled fiber array for phase distortions up to 180 hertz for each channel. The update rate of the computer-based SPGD controller is \( \sim 16,000 \) iterations per second. The average compensation bandwidth is about \( \sim 310 \) Hz.

Key words: phase locking, stochastic parallel gradient descent (SPGD), tiled fiber array, model free optimization

1. INTRODUCTION

Phase locking of adaptive tiled fiber array transceiver systems is a fast developing technique for compensation of the atmospheric aberrations in the free-space laser communications. Recently, some laboratory experiments which demonstrate the phase compensation effect of a 70-mm-diameter aperture transceiver that comprises a hexagonally close-packed array of seven 23-mm-diameter fiber collimator subapertures have been done in HRL Laboratories LLC, Malibu, California. In the experimental setup, the laser is fed into a 1X8 fiber beam splitter. Seven of the eight outputs of the splitter are respectively fed to seven fiber amplifiers which are driven by seven separate modulating pump lasers. Then the seven amplified laser signals, after modulations and polarization corrections in the optical fibers, are sent to the close-packed array of the seven fiber collimators, and next go to the free space. The modulations from the pump lasers are derived from a system performance metric acquired by a detector at the far-field receiver end and are performed by use of multidither feedback loops. The pump currents of the fiber amplifiers are updated up to tens of kilohertz. These experiments show that the feedback loop helps to compensate for the atmospheric aberrations by correcting the phase distortions [1].

More recently, the project of adaptive photonics phase-locked elements (APPLE) has been proposed in the Intelligent Optics Laboratory (IOL) of the U.S. Army Research Laboratory (ARL) through the U.S. Joint Technology Office (JTO). The basic transmitter architecture of APPLE is shown in Fig. 1. A multi-channel integrated polarization maintaining (PM) lithium niobate phase modulator manufactured by EO-Space Inc. is used to compensate for the atmospheric aberrations. The integrated phase modulators work in the low power range and only need control voltages as low as a few volts for \( \pi \) radian phase shift for each channel, which is an expected advantage. Also the phase modulator performs fast modulations up to GHz. The power capability is designed for more than one watt per channel. The high powers are achieved from all-polarization-maintaining Er/Yb-doped fiber amplifiers. The transmitter is compact, scalable, highly stable and low-noisy. The aberration compensation is based on the blind optimization of the received signal strength by using a stochastic parallel gradient descent (SPGD) feedback controller [2][3].

The schematic of phase-locking of the 7-channel tiled fiber array is shown in Fig. 2. After an optical wave is split into seven waves and further distorted by the atmospheric aberrations, we have seven distorted waves \( A_i e^{i\theta_i} \) \( (i = 1, \cdots, 7) \). The wavefront corrector applies phase shift \( e^{i\delta_i} \) \( (i = 1, \cdots, 7) \) to each channel, respectively.
The seven phase corrected waves, $A_i e^{j(\phi_i + \delta_i)} \; (i = 1, \cdots, 7)$ are combined to produce the resultant wave $\sum_{i=1}^{7} A_i e^{j(\phi_i + \delta_i)}$. The average intensity of the resultant wave is $J = \frac{1}{7} \left( \sum_{i=1}^{7} |A_i e^{j(\phi_i + \delta_i)}|^2 \right)$. Also the phase-locking maximized sum and not-compensated sum of the average intensity of the resultant wave are given as follows:

$$J_{\text{maximized}} = \frac{1}{7} \left( \sum_{i=1}^{7} |A_i|^2 \right)$$

and

$$J_{\text{not-compensated}} = \frac{1}{7} \left( \sum_{i=1}^{7} |A_i|^2 \right)$$

Denote the compensation gain $G = \frac{J_{\text{maximized}}}{J_{\text{not-compensated}}} = \frac{\left( \sum_{i=1}^{7} |A_i|^2 \right)}{\left( \sum_{i=1}^{7} |A_i|^2 \right)}$.

Fig. 1. Schematic of APPLE all-polarization maintaining fiber-component subaperture transmitter.

Fig. 2. Schematic of phase-locking of 7-channel tiled fiber array.
When the seven waves have identical intensities, the compensation gain is \( G = 7 \). In this ideal case, the compensation gain is equal to the total number of channels.

For the typical optical communications systems, the atmospheric aberration only has low frequency components up to a couple of hundred hertz. From this viewpoint, it is reasonable for us to choose low frequency simulating distortions up to 180 hertz in our phase-locking experiments for demonstration.

2. EXPERIMENTS

2.1. Experimental Setup

In Fig. 1, we show the schematic of the APPLE all-polarization maintaining fiber-component subaperture transmitter. However, it is difficult and time-consuming to align subapertures in parallel to a sufficiently high accuracy. In order to have good alignment, in our later experiments we may integrate active alignment control in the system. But at present, our first step is to demonstrate phase-locking without free-space optics.

The experimental setup of the phase locking of 7-channel tiled fiber array using SPGD feedback controller is shown in Fig. 3. The optical path starts from the laser. We use a diode laser, CQF935/508-19305, from JDS Uniphase with design wavelength 1552.93 nm, power limit 20 mW and the polarization-maintaining fiber-coupled output. Then a dual-stage polarization maintaining optical isolator from Novawave Inc. is connected to the laser through polarization maintaining fibers with a 90° change polarization adaptor in between. The optical isolator has polarization extinction ratio 18 dB and return loss 55 dB. The purpose of using the polarization adaptor is to rotate the polarization angle by 90° to cancel the extra 90° rotation of the polarization angles within the 1X8 phase modulator. After the optical isolator, a 1X8 integrated lithium niobate (LiNbO3) polarization maintaining phase modulator from EO-Space is connected through a polarization maintaining fiber. This phase modulator has 1 polarization maintaining fiber input, and 8 polarization maintaining fiber outputs. For our experiment we only use 7 channels, and the additional channel could be used for monitoring purpose. For each output, there is an electrical control terminal, through which the control voltage generated by the computer-based SPGD controller, after necessary amplification, is fed to modulate the phase of the specific channel. The phase modulator has a modulation bandwidth up to GHz. Also the phase shift has an approximately linear relationship to the control voltage for a specific channel with a control voltage of 3.0 volts for \( \pi \) radian phase shift for each channel. The channel loss discrepancy between different channels is less than 2.1 dB. The 7 output polarization maintaining fibers are connected to a similar EO-Space 8X8 polarization maintaining phase modulator which has 8 separate channels with 1 fiber input, 1 fiber output and an electrical control terminal for each channel. The 8X8 phase modulator is used to introduce the phase distortions to model the atmospheric aberrations. Although modeling of the atmospheric aberrations in this way is far from accurate, it is good enough to demonstrate the technical feasibility of phase locking in our experiments. The compensation bandwidth of this phase modulator is also up to GHz. The phase shift is also approximately linear to the control voltage with a control voltage of 1.55 volts for \( \pi \) radian phase shift. The extra insertion loss for each channel of this phase modulator is less than 3.4 dB. The 7 optical fiber outputs are combined by an integrated polarization maintaining beam combiner which is also from EO-space. The beam combiner is used to replace the receiver aperture in the free-space adaptive optics architecture. The insertion loss for each channel of the beam combiner is less than 1.8 dB. After combination, the light goes to a fiber-coupled beam collimator, passes through a polarizer, and then is split by a cubic non-polarizing 45:45 beam splitter. The transmitted branch goes to a CCD camera, and then goes to a TV for visual monitoring. The reflected branch goes to a photo detector, from which we get the system performance metric (the received signal strength) for feedback control. At this point, the optical path is complete. Attached with the two polarization maintaining phase modulators and the beam combiner are polarization maintaining fibers from OZ optics with the FC/PC standard connectors and insertion loss less than 0.3 dB. The design wavelength for the optical path is 1550 nm.

The primary electrical part of the experimental system is the feedback loop. The system performance metric acquired through the photo sensor is fed into the computer-based SPGD controller through the built-in A/D converter board, PCI-DAS1602/12. The SPGD control algorithm generates the updating control voltages, and then outputs the voltages through the built-in D/A converter board, PCI-DDA08/12. The control signals are amplified by the homemade multi-channel amplifiers with tunable gains. The gains are usually tuned to about 2–5 to keep the system working stably and efficiently. After amplification, the analog control voltages are applied to the 1X8 polarization maintaining phase modulator to compensate for the phase distortions introduced by simulating atmospheric aberrations introduced by the
8X8 phase modulator. The operating system of the control computer is Microsoft Windows XP Professional. This computer has a 3.4 GHz CPU and 1.0 GB DRAM. The update rate of the control voltages is about 16,000 iterations per second. The SPGD algorithm for the experimental system is further described in section 2.2 in detail. Another necessary electrical part of the experimental setup is the homemade distortion generators which comprise 7 independent sinusoidal signal generators. These signal generators have separate amplitude control, DC offset control and frequency control for each channel.

Fig. 3. Experimental setup of phase locking of 7-channel tiled fiber array using SPGD feedback controller

2.2. Stochastic Parallel Gradient Descent (SPGD) Algorithm

The generic stochastic parallel gradient descent (SPGD) algorithm described in [2][3] is customized below for our phase locking experiments of the 7-channel tiled fiber array.

Given cost function (the received signal strength),

\[ J(u_1, u_2, \ldots, u_7) \]

where \( u_1, u_2, \ldots, u_7 \) are amplified control voltages which are generated by the control computer. Each iteration cycle works as follows:

1. generate statistically independent random perturbations, \( \delta u_1, \delta u_2, \ldots, \delta u_7 \) where \( |\delta u_i| \) are small constants.
2. apply the control voltages with the “positive” perturbations and evaluate the cost function:

\[ J_+ = J(u_1 + \delta u_1, u_2 + \delta u_2, \ldots, u_7 + \delta u_7) \]

then apply the control voltages with the “negative” perturbations and evaluate the cost function:

\[ J_- = J(u_1 - \delta u_1, u_2 - \delta u_2, \ldots, u_7 - \delta u_7) \]

3. calculate the difference between the two evaluations of the cost function: \( \delta J = J_+ - J_- \)

4. update the control voltages, \( u_i = u_i + \gamma \delta u_i \delta J, i = 1 \cdots 7 \), where \( \gamma \) is the (adaptive or constant) update gain. In the present stage of the experiment, it is good enough to use constant gain in the algorithm to demonstrate the
compensation effect of phase locking. When $\gamma$ is positive, the cost function is maximally optimized for constructive interference; otherwise, minimally optimized for destructive interference.

2.3. Experimental Results

In the experiments, first we demonstrate the evolution of the phase locking of the 7-channel tiled fiber array. The transition curves from the constructive interference state (minimization) to the destructive interference state (maximization) of the system performance metric are shown in Fig. 4. In this figure, the average curve over 2000 real-time transition curves is shown and a few selected real-time transition curves are shown as well. From this figure, we see the average transition time, $\sim 6.25$ ms. For more techniques about the evolution curves from minimization to maximization, please refer to [4].

![Fig. 4. Transition Curves from minimization to maximization.](image)

Fig. 4. Transition Curves from minimization to maximization. [update rate: $\sim 16,000$ iters/sec, average transition time: $\sim 6.25$ ms, distortion magnitudes: 0.9 volts, distortion frequencies: 154 Hz $\sim$ 176 Hz]

The control voltage for $\pi$ phase shift is an important parameter for the optical phase modulator. Unfortunately, we do not have a direct method to measure the phase change corresponding to a control voltage. The schematic shown in Fig. 5 is used to estimate the control voltage for $\pi$ phase shift indirectly. The two individual phase modulators are channel #1 and channel #2 of the integrated 8X8 phase modulator for introducing the phase distortions to simulate atmospheric aberrations. The measurement can only give us the relationship of the output metric and the control voltage. Based on this schematic, we know that the interference part of the metric signal is a sinusoidal function of the phase change corresponding to a control voltage. Also it is very good to see the approximate sinusoidal waveform of the system.
performance metric versus control voltage as shown in Fig. 6 which is grabbed directly from the oscilloscope. From the waveform, we get an estimate of the control voltage, 1.55 volts, for π phase shift and the phase change is roughly linear to the control voltage after we make an appropriate DC offset of the control voltage. (see Fig. 7). This relationship exists in all 8 channels of the 8X8 phase modulator. For the 1X8 integrated phase modulator, the similar relationship exists. The only difference is that the control voltage for π phase shift is 3.0 volts.

Fig. 6. Metric J (vertical axis, arrow indicates 0V) vs. control voltage U (horizontal axis, arrow indicates 0V)

Fig. 7. Channel response curve of the 8X8 integrated phase modulator

Fig. 8 shows the performance degradation with respect to distortion voltage magnitudes (or phase shifts) for the seven channel tiled fiber array phase locking system. The distortion frequencies are still kept in the range from 154 Hz to 176 Hz as before. But the distortion magnitudes are increased gradually from 0.0 volts to 9.0 volts. The curve shows that with higher magnitudes of the distortions, the system performance metric is degraded. The degradation effect is from the fact that more control iteration cycles are needed for larger distortions. However, when larger distortions are applied, the computer-based SPGD controller runs at the same speed. That’s where the degradation comes from. The -3 dB point is at ~ 1.2 π radian phase shifts. Also in this figure we use the approximately linear relationship between the phase change of the optical phase modulator and the control voltage in the working range applied to it as discussed above to draw the double horizontal axis.
The performance degradation with respect to the distortion frequencies for the 7-channel tiled fiber array phase locking system is shown in Fig. 9. To acquire this curve, the distortion magnitudes for all channels are fixed at 1.55 volts (π rad. phase shift). The distortion frequencies are increased from DC to about 2000 hertz. The curve shows that the phase locking compensation system has a compensation bandwidth of ~310 Hz (-3 dB point).

To evaluate the compensation gains, we measure the output powers (Fig. 10) of all seven individual channels separately. Sum the measured values channel by channel algebraically, and we have the not-compensated sum of the system performance metric given the total number of channels. Calculate the square roots of these individual outputs, add them up and square the sum, we get the corresponding calculated maximized sum of the intensity of the system performance metric. Also we measure the maximized sum of the system performance metric directly from the experiments. The experimental maximization state is acquired this way: remove all the distortions, and then maximize the system performance metric, which is the measured maximization sum. Following the description of the compensation gains in the introduction, we get the measured compensation gain and the calculated compensation gain. Repeat this procedure for total number of channels from 2 to 7, and we get the curves in Fig. 11 and in Fig. 12. The ideal compensation gain, which is equal to the number of channels described in the introduction, is also plotted in Fig. 12 for reference. Obviously, for a given number of channels, the measured compensation gain is no bigger than the calculated
compensation gain which is in turn no bigger than the ideal gain. Even with the channel loss discrepancy shown in Fig. 10, the three compensation gains for a specific total number of channels are still close to each other. The discrepancies between the measured and calculated compensation gains are probably from the polarization mismatches and the residual phase errors between different channels.

![Fig. 10. Measured individual channel output powers](image1)

![Fig. 11. Measured and calculated metrics vs. number of channels](image2)
CONCLUSION

We have demonstrated the technical feasibility of phase locking of the 7-channel tiled fiber array using SPGD feedback controller. The update rate of the SPGD controller is about 16,000 iterations per second and the average compensation bandwidth is about 310 hertz. The experimental results we described in this paper are a first step toward the demonstration of free-space communications systems with an active multi-channel subaperture transmitter, and an active multi-channel subaperture receiver. In our further experiments, we will replace the Microsoft Windows computer-based SPGD controller with a dedicated real-time SPGD controller combining faster A/D, D/A converters and VLSI techniques to boost the control speed. For the fiber optics part, we will integrate individual channel loss control (adding optical fiber attenuators) and active polarization control to gain better performance. Also in order to implement the system in free-space adaptive optics easily, we will use active alignment control (with the help of fiber actuators) for the multi-channel subaperture transmitter or receiver or both to overcome the alignment problem related to the multiple fiber collimators. With these new features, we expect promising applications of this system in the future.

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