Long Distance Broadband Fiber Optical Beamforming over 120 km

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ABSTRACT

With the development of the space exploration and satellite communications, the data transmission at broadband and long distance are in increasing demand. To enhance the signal transmission capability from the satellite to the earth over deep space, multiple radars from distributed ground stations at cooperative mode might be a promising solution. Broadband beamforming with high efficiency over long distance fiber optic transmission links is investigated in the paper. To achieve phase stable transmission for broadband signal, fast active optical compensation is adopted by phase locking each fiber optic link with a separate wavelength to discriminate the time jitter induced phase variation. By matching the time delays between the different channels, the signal-noise ratio (SNR) of the beamformed broadband signal is improved significantly. In the experiment, a root mean square (RMS) of time delay variations of 0.86 ps and Allan deviation of $1.74 \times 10^{-13}$ for the carrier transmission in the phase locked fiber link over 120 km is achieved, and broadband fiber optical beamforming with data rate over 2 Gbit/s is successfully demonstrated.

INDEX TERMS

Broadband signal, optical beamforming, time jitter compensation

I. INTRODUCTION

The evolution of satellite systems and promising space missions such as gravitational wave and black hole detection has shown a trend towards satellite communications with broader bandwidth [1]–[3]. On the one hand, the wide operating bandwidth communication means that satellites systems can provide wider communication coverage and data connections [4], [5]. On the other hand, multiple radars on the ground can also utilize a multi-channel broadband system, from which more accurate and diverse sensing information can be extracted [6]. These are of great importance for advanced satellite missions. Therefore, how to maintain the phase stability of transmission data received from radars between the different base stations over long distances and how to improve the efficiency of broadband beamforming are bottlenecks which need to be overcome [7].

The conventional implementations of high-efficiency beamforming using microwave devices such as electrical mixers, frequency multipliers as well as phase shifters, have disadvantages of limited frequency bandwidth, complex system, and sensitivity to electromagnetic interference [18]–[20]. Therefore, several optical pioneering beamforming schemes have been proposed [8]–[15]. The beamformer based on a ring resonator provides an effective way to obtain a compact and squint-free structure. In addition, the phase of modulated optical signals can be stabilized by the hybrid integration of modulators [8], [15]. However, the present photonic chips with ring resonators are suffered from the high insertion loss and the restricted operating bandwidth. Some beamformers based on ring resonators are combined with optical switches to realize wider bandwidth and continuous delay tuning [9]. Nevertheless, the main challenge is the fabrication error which limits the accuracy of the tuning increment [10]. The linearly chirped Bragg grating beamformer has been adopted to further improve the broadband capability and tuning range [11], [12]. However, the limitations of these methods based on thermal or mechanical tuning are arisen by their low switching speed of true time delay (TTD) [13]. Moreover, the stability of the system employs mechanical tuning is poor. Some beamformers employ special fibers with high dispersion and tunable light sources to achieve flexible multiple-beam transmitting and receiving [13], [14]. Although these schemes have realized large tuning scale, the system structure using multi-wavelength laser arrays seems complexed and the innate high-order dispersion obstructs the
broadband beamforming for high capacity radar signals [15]. Recently, the integrated optical beamforming networks are recognized as the promising technology in wideband systems [21]–[22]. For example, a delay of 0.49 ns with a bandwidth of 10 GHz targeting X-band antenna was reported [23]. Compared with the non-integrated solutions, the integrated optical beamforming networks have much lighter weights and higher carrier frequencies [21]. However, the current integrated photonics solutions usually suffer higher insertion loss, the TTD networks as in [21]–[23] only support discrete delays and the precise control of all the switches in the network is necessary, which seems complicate.

In this letter, a scheme for broadband long distance optical beamforming is proposed and experimentally demonstrated. To achieve the phase stability of the broadband signal, the time jitter of long distance fiber is discriminated through phase locking of transmission link with a separate compensation, and broadband fiber optical beamforming transmission link with the applied fast active optical

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where $m_1$ is the modulation depth of the reference signal, $m_2$ is the modulation index of the RF signal, $J_n$ is the n-th order Bessel function of the first kind.

When the modulated light double passes the long fiber link, the phase of the signal is affected by the fiber link. At the output of PD2, the upper sideband electrical signal can be written as

$$V_o(t) \propto \cos(\omega_{RF} + \omega_{RF} + \omega_{RF})(t + \tau_{com} + \tau_{link})$$

where $\tau_{com}$ is the TTD generated by OTDL, and $\tau_{link}$ is the back and forth time delay induced by the long fiber link.

When the output electrical signal of PD2 is mixed with the RF signal and filtered by BPF, the recovered signal with the phase drift of the fiber link can be expressed by

$$V_c(t) \propto \cos(\omega_{RF} + \omega_{RF} + \omega_{RF})(t + \tau_{com} + \tau_{link})$$

The phase difference $\Delta \phi$ between the reference signal and the recovered signal given by Eq. (3), can be written as

$$\Delta \phi = (\omega_{RF} + \omega_{RF})(\tau_{com} + \tau_{link})$$

Then, the phase difference $\Delta \phi$ is integrated into a PID regulator module to control the OTDL in the link. From Eq. (4), when $\Delta \phi$ keeps zero or a constant by precisely and quickly adjusting the $\tau_{com}$ of OTDL, the phase variation of the transmission link can be well corrected to achieve stable phase transmission.

In the main transmission path, assume the MZM1 is modulated by a quadrature phase shift keying (QPSK) signal generated by the corresponding remote antenna, which can be represented as $\cos[\omega_i r + \theta(t)]$, where $\omega_i$ is the frequency offset of the QPSK signal, $\theta(t)$ is the modulated phase of the carrier. After the modulated optical signals at wavelength $\lambda_1, \lambda_2$ are transmitted through the long fiber link and then multiplexed by WDM3, the optical signal can be expressed by

$$E_j(t) = \sum_{n=1}^{N} \exp \left( \frac{2\pi i n}{\lambda_n} - \pi + \beta_n \cos(\omega_i t + \theta(t) + \Delta \phi) \right)$$

where $\beta_n$ is the modulation depth of the transmission signal, $\Delta \phi$ is the remaining phase of different channels after active compensation, and $n$ is the number of the channels.

After being detected by PD1 and ignoring beat frequencies between different wavelengths, the power of beamforming broadband signal can be expressed by

$$J_s = R \cdot E_j(t)E_j(t)^*$$

where $V_i$ represents the voltage of the modulated signal in different channels, $R$ is the responsivity of the PD1, and $\Phi$ is a constant generated by formulas of trigonometric functions.

### III. EXPERIMENTAL RESULTS AND ANALYSIS

A proof-of-concept experiment is carried out as shown in Fig. 1, and a two-channel beamforming structure is set up for the experiment. The transmission broadband signals are generated by an arbitrary waveform generator (AWG) to simulate the broadband vector signal received from the antennas, and the modulated signal power of each channel is kept at the same level. The wavelength of LD2 is 1558.1 nm, while the beamforming wavelengths $\lambda_1, \lambda_2$ are 1551.086 nm, 1554.08 nm, respectively. The center wavelength of the OBPF is 1558.1 nm and the bandwidth of the filter is about 0.8 nm. The EDFA with optical gain of 28 dB is used to compensate the optical loss the link. An oven controlled crystal oscillator (OCXO) with a frequency of 100 MHz is equally power-divided into two parts. The DDS receives one part of the OXCO signal to generate the reference signal of 150 MHz. And the BPF with a center frequency of 150 MHz is adopted to select the upper sideband signal with phase drift output by the mixer. The other part is used as the reference signal of PLL, which provides an output 10 GHz RF signal. The PD1 is same as the PD2 in bandwidth of 12 GHz and responsivity of 0.65 A/W.

![FIGURE 2](image)

**FIGURE 2.** Time delay variations of the beamforming RF signal at 5 GHz over 120 km optical link without and with active compensation in 15 minutes.

Fig. 2 shows the time delay variation of the beamforming of a single tone of 5 GHz signal generated by Keysight N9952A without and with the active optical compensation. The time delay variation without compensation has 126.8 ps within 15 minutes, which is mainly caused by the environment temperature variation. While the fast active compensation is applied in the transmission link, the RMS...
delay variation can be suppressed to less than 0.86 ps. The green line in Fig. 2 is a zoom view of the time delay variation with compensation. However, there is still about a ±2 ps peak-peak drift. The main reason is some sections of optical fibers used to connect lasers and WDMs are out of the compensation loop and subject to the ambient temperature change. The frequency stability of the transmitted single-tone with and without fast active compensation by overlapping ADEV and phase noise spectrum are evaluated under the same experimental conditions. As can be seen from Fig. 3, the beamforming link without compensation shows frequency drift and behaves divergence, while the overlapping ADEV of with compensation behaves convergence, reaching 1.74×10^{-13} at 1000 s. Fig. 4 shows the phase noise spectrum measured by the R&S FSW-67 ESA. Compared with the phase noise without compensation, the phase noise with compensation is averagely suppressed by 7 dB within the 4 Hz frequency offset, and the accordingly time jitter is only 0.34 ps shown in the red line. Considering a 3 dB uncertainty of the instrument, the phase noise with compensation and without compensation are almost the same as at 1 kHz to 100 kHz. In addition, it is worth noting that the spurs at 27 Hz, 1 kHz are caused by the signal generator itself. However, the compensation has little effect on the phase noise at the frequency offset beyond 4 Hz. This result shows that the bandwidth of the feedback control is about dozens of Hz, which can be improved by using the faster method of controlling the OTDL.

![FIGURE 3. Overlapping ADEVs of the beamforming 5 GHz signal with and without phase compensation.](image)

The beamforming signal of two-channel with a different phase difference (Δφ1 - Δφ2) is shown experimentally. The QPSK signals with a frequency offset of 5 GHz and bits rates of 20 Mbit/s are applied to the modulators in two transmission links at the same power level. The differential delay between the two channels can be changed by adjusting the TTD of two OTDLs. The SNR of the single channel output is only about 29 dB shown by the pink line in Fig. 5. When the phase difference is 90° or 270°, it is can be seen from Eq. (6) that the output power is increased by 3 dB shown by green and blue lines in Fig. 5. When the phase difference between the two channels is nearly matched, the SNR of the beamforming signal is 35.6 dB without an electrical amplifier shown by the red line. Compared with the SNR of the single channel, the SNR of the beamforming signal can be improved by 20log2 dB by accurately delay matching between different channels.

![FIGURE 4. Phase noise spectrum of fiber link with compensation (red) and without compensation (blue) and back-to-back link (green).](image)

![FIGURE 5. The output electrical spectrum of 5 GHz QPSK signal with symbol rates of 20 Mbit/s in the case of different phase differences between two channels.](image)
The broadband beamforming capability of the scheme can be reflected by the maximum bits rate of the beamforming signal and 4 Gbit/s QPSK signal with a frequency offset of 5 GHz. With the help of a low noise electrical amplifier and two-channel delay match, the SNR of the 2 Gbit/s signal reaches 36.45 dB, and the SNR of the 4 Gbit/s signal is 32.72 dB. Fig. 6(c) shows the clear constellation diagram of 2 Gbit/s QPSK signal, and the error vector magnitude (EVM) is calculated to be about 12.05%. The demodulation effect of the 4 Gbit/s QPSK signal is not as good as the 2 Gbit/s QPSK signal, and the EVM is about 19.121%. Since the QPSK signal power directly generated by the AWG is relatively low, two electrical amplifiers are placed after the AWG and the PD1 to improve the output power. Slight rotations of the constellation diagram of the demodulated signal observed in Fig.6 are mainly caused by the phase noise introduced by the laser diodes and the effect of dispersion of fiber link, as discussed by [24]. Fig. (7) shows the EVM results and constellation diagrams versus different symbol rates of transmission signal at 5 GHz. The results show that the broadband fiber optical beamforming over 120 km with a data rate over 2-Gbit/s is successfully demonstrated.

**FIGURE 6.** (a). Electrical spectrum of 2 Gbit/s QPSK signal with dual-channel beamforming. (b). Electrical spectrum of 4 Gbit/s QPSK signal with dual-channel beamforming. (c). The constellation diagram of 2 Gbit/s QPSK signal after demodulation. (d). The constellation diagram of 4 Gbit/s QPSK signal after demodulation.

**FIGURE 7.** EVM results and constellation diagrams versus different symbol rates of transmission signal at 5 GHz.

**IV. CONCLUSION**

In summary, a scheme for long distance optical broadband beamforming is proposed and demonstrated. The scheme achieves phase stable transmission by phase locking to a separate wavelength with the adoption of a fast OTDL as active optical compensation. In addition, the time delay between two channels can also be matched by the OTDL, so as the SNR of the beamforming signal is improved. An RMS of time delay variations of 0.86 ps and ADEV of 1.74×10^{-13} show the high stability of long distance transmission links, and broadband fiber optical beamforming over 120 km with data rate over 2-Gbit/s is also realized experimentally. In the future, this scheme has great potential in satellite-ground communication and multiple-radar systems.

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