Research on Coherent Light detection Method Based on Phase Control of Fiber Delay Line

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Abstract. With the system modeling and simulation, analyzed the mechanisms of signal transmission and storage, and phase-controlling, and researched the relationship between time-delay and phase-delay. The effect of optical path difference on optical phase-matching is investigated in time domain and frequency domain. The results shows that, the signal power will obtain maximum after coherent mixing when the phase between signal light and reference light is 2nπ (n=0, 1, 2......); the signal power will obtain minimum when it is (2n+1)π (n=0, 1, 2......), and the mixing signal of other phase relationship will vary in this range. And it is proved that the time delay of optical fiber delay line could effectively compensate the phase delay which generated in the transmission and a phase controlling of the signal transmission could be achieved.

1. Introduction
With the increasing maturity of optical fiber technology, the fiber delay line has been a new signal processing device, it has evolved from a simple piece of optical fiber to an independent device with a variety of complex structures at this stage, and can be made up of lots of optical signal processing device, and it gradually become one of the keys to optical signal processing[1]. We can realize the precise control of phase and promote the optical signal processing by using fiber delay line. Aiming at the characteristics of the traditional coherent optical detection system that the phase is random and difficult to control, this paper discusses a fiber phase control coherent detection method, which uses the signal transmission characteristics of the fiber delay line, based on the optical path difference control, according to the phase relationship of the coherent optical detection signal, constructed a coherent optical detection system, combined with theoretical simulation and experimental testing to verify the feasibility of the system implementation. Realize the best matching of coherent light detection phase, and further improve the coherent receiving performance of the system by using phase control in fiber delay line and adjusting the phase difference between light and signal light.

2. Transmission characteristics of fiber delay line signal
Fiber delay line is the optical fiber or the passive optical network which can delay the transmission of optical signal, what is the most basic application is delay unit. it can realize the delay we need by
using optical signal control, optical signal can be transmitted and delayed by optical fiber. It has the characteristics of small size, large bandwidth, strong anti-interference ability and high delay accuracy[2].

When optical signal through the fiber delay line, its amplitude, polarization direction and frequency do not change, it just delay the transmission for a while. The optical signal is instantly stored in the fiber delay line unit, and the storage time is proportional to the optical path length. According to the principle of optical transmission, if the dispersion problem is not considered, if the fiber length is L and the refractive index is n, when the optical pulse signal is transmitted in the fiber at group speed, the optical signal delay time $\Delta \tau$ can be expressed as[3]:

$$\Delta \tau = \frac{L}{v_g} = \frac{Ln}{c}$$

(1)

Where $c$ is the speed of light propagation in a vacuum. According to (1), the length of the delay time is proportional to the fiber length L. So, we can get different delay time by controlling the optical signal through the different light path.

3. Coherent detection optical phase matching and control detection efficiency

The principle of coherent light detection as the Figure 1 shows:

![Figure 1. The principle of coherent light detection](image)

The signal light transmitted by the transmitting end reaches the receiving end, and is incident on the photosensitive surface of the photodetector together with the local oscillation reference light for coherent mixing, and the photovoltaic conversion is realized by mixing in the photodetector. The frequency output signal can be describe as[4]:

$$i_{ip} = \alpha \sqrt{P_sP_L} \cos[(\omega_s - \omega_L)t + (\varphi_s - \varphi_L)]$$

(2)

Where $\alpha = \frac{n_\epsilon}{h\nu}$ is photoelectric conversion constant, $P_s$ and $P_L$ are the average optical of signal light and reference light respectively, $\omega_s$ and $\omega_L$ are the angular frequency of signal light and reference light, $\varphi_s$ and $\varphi_L$ are the phase of signal light and reference light. It is called heterodyne detection when $\omega_s - \omega_L \neq 0$; when $\omega_s - \omega_L = 0$, it is homodyne detection. The condition(2) of the formula is the wavefront of the signal light and the reference light must maintain a certain frequency and phase relationship in addition to the same polarization state on the entire photosensitive surface of the detector[5]. When the frequency and phase change, the intermediate frequency output of coherent detection will also change.

There are some inevitable phase change when signal in transmission, it will influence the system mixing effect. The phase difference will continuously vary from 0 to $2\pi$ with the propagation distance
in the optical device and the system, when the phase difference is $2n\pi$ between signal light and reference light, after overlaying phase length and coherent mixing we will reach the max of signal; When the phase difference between the signal light and the reference light is $(2n+1)\pi$ ($n=0, 1, 2\ldots$), the superposition is cancelled, and the signal obtained after coherent mixing is the minimum. The detected signal changes continuously with a period of $2\pi$ between the minimum and maximum values as the phase difference changes between 0 and $2\pi$.

Because the frequency of light is extremely high, its phase cannot be accurately controlled, and it is relatively simple to convert phase control to time control to compensate for the phase delay caused by the signal in the transmission process. Assume that a signal is

$$E_\lambda = A\cos(\omega t)$$

it will produce some minor phase changes and phase delay $\Delta \varphi$ when optical instrument in transmission, finally it will turn to

$$E_{\lambda(t)} = A\cos(\omega t + \Delta \varphi) = A\cos(\omega (t + \Delta \tau))$$

Where $\Delta \tau$ is the time delay of insteading phase difference. In

$$\Delta \tau = \frac{\Delta \varphi}{2\pi f} = \frac{\Delta \varphi}{2\pi} T$$

we can know that

$$\Delta \varphi = \frac{2\pi \Delta \tau}{T}$$

where $T$ is the cycle of signal.

What can we learn from (1) and (6) is adjusting the delay of the optical path change time through the optical fiber delay line can realize the phase control, solve the phase mismatch phenomenon caused by the signal in the coherent communication transmission process, thereby improving the sensitivity and signal-to-noise ratio of coherent detection, and reducing the zero to a certain extent. The difference detects the influence of the optical path difference on the phase synchronization.

4. Modeling and Simulation of Coherent Detection System

As the Figure 2 shows Use the optisystem15 platform to build a coherent optical detection system based on the phase control of the optical fiber delay line, and provide a reference for experimental testing through simulation.

![Figure 2. Simulation model](image)

Set the optical wavelength of the fiber laser to 1550nm, power to 10dBm, and line width to 10MHz. It is divided into signal light carrier and reference light by the coupler, and the system uses homodyne
detection of the same origin. Set the optical power of the signal optical branch to 9mw (9.5dBm) and the reference optical branch to 1mw (0dBm). The modulator uses a sine signal with a frequency of 10 GHz to modulate, and appropriately controls the power of the input RF signal to avoid intermodulation of the signal after modulation [6]. By changing the delay time of the optical fiber delay line to control the phase difference with the reference optical branch, then the two signals are coherently mixed and received by the PIN photodetector to complete the photoelectric conversion, and analyze and receive from the frequency domain and time domain respectively to the signal.

In the simulation, the phase of the reference optical branch signal is used as the reference. According to the adjustment accuracy of the optical fiber delay line, the interval unit is 0.1ps. When the delay varies from 0ps to 10ps, the 10GHz signal power output by the system output B will increase with the delay time. The change is cyclical, and the maximum value is obtained around the delay of 1.5, 3.7, and 5.6ps. The same change rule can be obtained by controlling the delay of the reference optical branch by the optical fiber delay line in the simulation.

After the photoelectric conversion of the simulation system is completed, a 45dB amplifier is added, and the bandpass filter with a bandwidth of 5GHz is added to observe the signal frequency domain and time domain of output point C. The signal frequency domain waveform is shown in Figure 3.

In the figure, when there is no phase control (without delay line), the signal power value of the system output C is about 21.76dBm, as the delay amount increases, the output signal power increases. When the delay is 1.5ps, the signal power reaches 24.76dBm. Output in two states shows the power spectrum is the same, only through the phase control of the optical fiber delay line, the power spectrum of the received signal is improved compared with the case without phase control.

What can we know from the consequence is that in the same condition, when the delay amount are 1.5, 3.7, 5.6ps, it is best match for phase. As long as the phase difference between the two branches is $2\pi$, the signal power output by the coherent optical detection system will reach the maximum, and the sensitivity is improved by 3dB compared with the phase control without delay line. The same effect can be obtained for the time domain measurement waveform.

5. Analysis of Optical Fiber Delay Line in Coherent Detection System
According to the consequence of simulation and system-related realization conditions, we build this experimental test platform as the Figure4 shows.
Figure 4. Experiment system

Experiment system consists of four parts, fiber-optic laser, modulator, fiber delay line and Photoelectric detection module. The fiber laser is a single-frequency laser with a center wavelength of 1550nm, an output power of 25mw, and a line width of 25KHz. The output laser beam is divided into signal light and reference light by a 1*2 polarization maintaining fiber splitter. The signal light is sent to the phase modulator, which has a working wavelength of 1550nm and a bandwidth of 20GHz. The RF signal is loaded into the modulator, and the output signal light is controlled by the optical fiber delay line to generate the phase control signal, and then sent to the 1*2 combiner and reference light for combined transmission and coherent mixing. Finally, the PIN photoelectric detection module completes the photoelectric conversion and amplification.

During the test, set the delay of the optical fiber delay line to 0ps (the delay line is not used) and 1.5ps (the maximum value) in the simulation results, and the output spectrum after observing the system is shown in Figure 5.

As the figure shows that the output power is 21.76dBm when the delay line is not connected, and the output power is 24.77dBm when the delay is 1.5ps. From this result, it can be seen that by appropriately performing the optical path control of the signal light and the reference light through the fiber delay line, the best detection of the system can be obtained.
6. Conclusion

Building the coherent light detection system by the phase controlling of fiber delay line, we researched the relationship between time-delay and phase, according to the experiment and simulation of optisystem, we investigated the influence of phase difference to optical phase matching in time domain and frequency domain, the result shows that the coherent light detection system adopting phase control, as long as the phase relationship of the two coherent light satisfies $2\pi n$ ($n=0, 1, 2...$), its receiving sensitivity can be improved by almost 3dB, which further proves the feasibility of the system and is practical and the application provides a reference basis.

Acknowledgments

The study was supported by the National Natural Science Foundation of China under Grant No.61764002, Guangxi Natural Science Foundation under Grant No.2017GXNSFAA198282, the Innovation Project of GUET Graduate Education under Grant No.2019YCS003, and the Study Abroad Program for graduate student of Guilin University of Electronic Technology under Grant No.GDYX2019007.

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