All Fiber Double-Balanced Laser Coherent Detection System

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ABSTRACT

Laser coherent detection makes use of the coherence of laser to pick up weak laser signal by an optical LO (local oscillator) signal. Compared to direct detection, coherent detection has higher sensitivity and could get the frequency difference between incident signal and LO. Traditional coherent detection systems are composed of free space optical components; the systems were complicated and hard to adjust. We built an all-fiber MOPA heterodyne laser detection system by DFB laser, AO frequency Shifter, polarization beam splitters, polarization maintaining couplers and balanced photo receivers. Because the coherence of laser beams is relative to the alignment of polarizations states, our system uses double-balanced structure. The balanced detection structure greatly reduces the relative intensity noise of the LO. In the article, the theory of coherent detection and the double balanced coherent detection are presented; the design of detection electronic circuits is also discussed. The high coherent efficiency of fiber-optic detection system and high sensitivity of coherent detection are proved by experiment. Some problems caused by fiber optics are also introduced.

Keywords: Laser, Coherent Detection, Fiber-optics, Balanced Photoreceiver

1 INTRODUCTION

Laser coherent detection has many merits, such as high sensitivity and the ability to detect frequency and phase change of incident signal. At the same time, many disadvantages should not be neglected, coherent detection has complex optics, and it's sensitive to the state of polarizations, the coherence efficiency is determined by space collimation of laser beams. Because of the development of optical fiber communication, many kinds of fiber optical components appeared, which make all-fiber optical system possible. The aim of this system is to measure weak laser signal by coherent detection. In the system, commercial fiber-optical components are used to build the coherent optic system, which is light and robust and almost don't need adjustment. The experiment proved that fiber-optics system could reach high coherent efficiency.

2 DOUBLE BALANCED COHERENT DETECTION

2.1 Theory of Coherent Detection

When a photo detector such as PIN diode or ADP receives a beam of mixed light of a local oscillator $E_{loc} = A_{loc}\cos\omega_{loc}\,\mathrm{t}$ and the incident signal $E_{in} = A_{in}\cos[\omega_{\mathrm{in}}\,\mathrm{t} + \phi(t)]$, E_{loc} and E_{in} are optical electromagnetic fields, the output current I_1 from the detector is shown in equation (1).

$$I_1 = R\{P_{in} + P_{loc} + 2h_c\sqrt{P_{in}P_{loc}}\cos(\gamma)\cos[(\omega_{in} - \omega_{loc})t + \phi]\} \tag{1}$$

I_1 contains the direct detection signal of LO and incident signal $R(P_{in}+P_{loc})$ and the heterodyne signal of LO and the

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heterodyne signal $2Rh_c\sqrt{P_{in}P_{loc}}\cos(\gamma)\cos[(\omega_{in}-\omega_{loc})t+\phi]$. The amplitude of heterodyne signal is decided by the power of two signals the coherent degree coefficient h_c, and γ is the angle between polarization axes of the LO and the incident beams. If h_c and cos (γ) are constants and the power of LO is known, the power of incident signal could be known.

Getting high coherent degree coefficient needs space collimation of two beams; wavefronts matching; the same cross section area of two beams, and the beams should be vertical to the surface of detector. Polarization axes of the incident beams should be parallel. Tiny optical mismatch would affect the heterodyne signal greatly, which make the free space optical system of coherent detection complicated and hard to adjust. The fiber optics resolves this problem by restricting lights in the fiber to keep space collimation.

According to the equation (1), strong LO is needed to pick up weak signal. Strong LO makes the RIN (relative intensity noise) and shot noise of LO main noise source. As the heterodyne detection of RF signal, balanced detection is introduced to reduce the impact of RIN. Balanced detection employ two LO signals to mix with incident signal separately. There is a 180° phase difference between the two LOs. The structure of balanced detection by fiber-optics is shown in Fig.1, composed by 50/50 fiber coupler and balanced photo receiver.

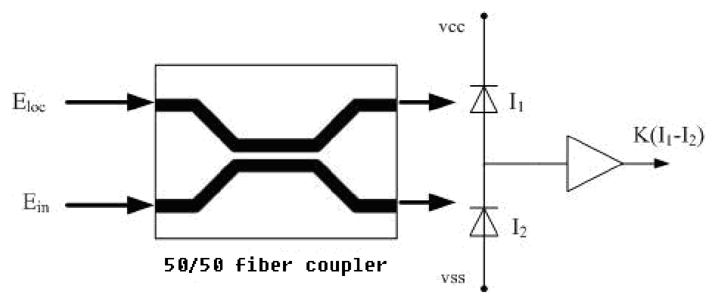

Fig.1 Balanced Detection

Fiber coupler has four ports, two as input to receiver LO and incident signal, the other as output. The 50/50 fiber coupler can be represented by a 2X2 matrix as:

$$\overline{H}=\frac{1}{\sqrt{2}}e^{j\theta}\begin{pmatrix}1 & 1\\ 1 & -1\end{pmatrix} \tag{2}$$

According to the matrix, signal from each input port would be separated to two output ports equally, but one coupled arm of the coupler brings an added 180° phase delay. If the optical electromagnetic fields of LO and incident signal is E_{loc} and E_{in} (P_{loc} and P_{in} as their power) , the outputs from the coupler are(omitting the phase delays that are same to each port):

$$E_1=\frac{1}{\sqrt{2}}\left(E_{in}+E_{loc}\right) \qquad\qquad E_2=\frac{1}{\sqrt{2}}\left(E_{in}-E_{loc}\right) \tag{3}$$

Mixed signal E_1 and E_2 injects into one PIN detector of the balanced photo receiver separately. Because of the square law of photo detector, the output currents of PIN detectors are:

$$I_1 = \frac{1}{2} R\{P_{in} + P_{loc} + 2h_c \sqrt{P_{in} P_{loc}} \cos(\gamma) \cos[(\omega_{in} - \omega_{loc})t + \phi]\} \tag{4}$$

$$I_2 = \frac{1}{2} R\{P_{in} + P_{loc} - 2h_c \sqrt{P_{in} P_{loc}} \cos(\gamma) \cos[(\omega_{in} - \omega_{loc})t + \phi]\} \tag{5}$$

Balanced photo receiver outputs the current difference between two PINs, the actual balanced photo receiver also contains a transimpedance amplifier, changing the current into voltage and offering gain. So the signal from the balanced photo receiver is (K: the transimpedance gain):

$$V_{out} = K * (I_1 - I_2) = 2K * Rh_c \sqrt{P_{in} P_{loc}} \cos(\gamma) \cos[(\omega_{in} - \omega_{loc})t + \phi] \tag{6}$$

As the equation (6), balanced detection eliminates the direct detection part of the signal, greatly reduces the impact of RIN. At the same time, the optical structure isn't complex, only a 50/50 fiber couple and balanced photoreceiver is needed.

2.2 MOPA Configuration

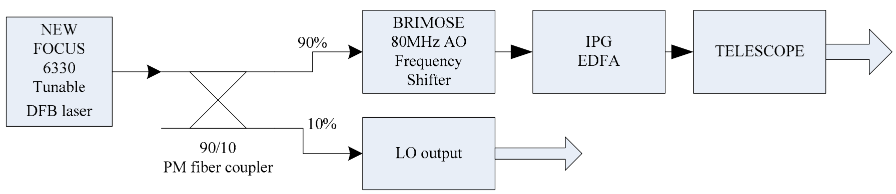

Fig.2 MOPA（master oscillator power amplifier）

In coherent detection, the wavelength of LO and incident signal can be the same. And the heterodyne signal became a DC signal decided by the phase difference between two signals which is harder to process. So, a fixed frequency difference should be brought in as the intermediate frequency. The fixed frequency difference can be produced by two lasers. This method needs two lasers to maintain the fixed frequency difference, which is hard to implement. The convenient method is to employ MOPA (Master Oscillator Power Amplifier) configuration. Single laser work as master oscillator, part of the output is used as LO, the other part is injected into AO frequency shifter. This part signal is amplified by EDFA and sent to the target. The MOPA configuration is shown in Fig. 2.

2.3 Double-Balanced structure

Double-Balanced coherent detection separate the LO and the incident signal into two orthogonal polarization axes, coherent detection would be realized by signals having the same polarization state, so the impact of incident signal's unknown polarization state on the coefficient cos (γ) would be eliminated.

All fiber-optical components in Fig.3 must be polarization maintaining components; otherwise, the polarization state would change along the optical system. The fiber PBS split the LO and incident signal into two polarization axes, of which one is parallel with the slow axis of the PM fiber and the other vertical. The laser in the system (New Focus TLB-6330) is in single mode and linear polarized along slow axis. Accommodation of the polarization state is needed to divide the laser into two orthogonal polarization states. The adjustment is to rotate the linear polarization axis 45°, and the laser would be divided equally. The PM couplers and PBSs in the system are sensitive to wavelength of the laser. If the wavelength isn't suitable, the performance of the components would degrade, especially for the PM coupler, its division rate is relative to the wavelength. If the division rate isn't 50/50, the additional phase change in the coupler is not 180°, which would depress the performance of balanced detection.

According to equation (6), the amplitude of output intermediate frequency signals of two sets of balanced detection are:

$$A_{outv} = 2K * Rh_{cv}\sqrt{P_{inv}P_{locv}} \qquad A_{outvh} = 2K * Rh_{ch}\sqrt{P_{inh}P_{loch}} \tag{7}$$

A_{outh}, A_{outv} : IF signal amplitudes of slow and fast axis; P_{inh}, P_{inv}: incident signal power along slow axis and fast axis; P_{loch}, P_{locv}: LO power along slow axis and in fast axis; h_{cv}, h_{ch}: coherent coefficient.

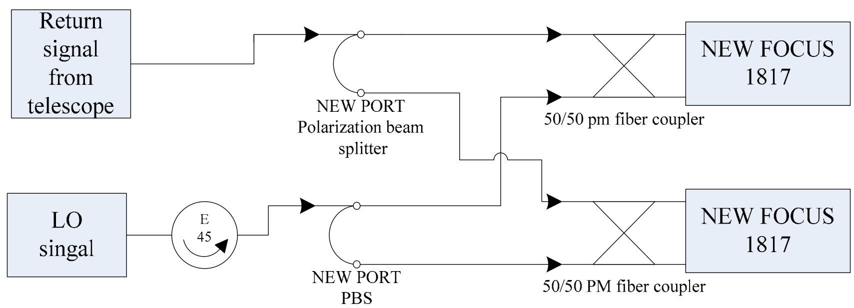

Fig.3 Double balanced coherent detection structure

Assuming the characteristic of the detectors and the optical components is uniform, h_{cv} and h_{ch}, P_{loch} and P_{locv} are the same. If the amplitudes of IF signals could be measured, the power of incident signal is known by the sum of squares of IF amplitude.

3 ELECTRONIC CIRCUIT

The detection electronic circuits comprise two parts: IF signal conditioning part and DAQ part. Signal conditioning part amplifies the IF signal and eliminate noise by SAW band pass filter, then changes the amplitude of AC IF signal to a voltage. The DAQ part converts the voltage into digital signal and sends to the computer.

3.1 Signal Conditioning Part

The structure of the circuit is shown in fig.4. The circuit includes three stages, the front stage composed by LNA ADL5530, the mid-stage by VGA AD8332 and the radio detector part by LTC5507. LNA is employed to reduce the noise figure of the whole amplifier. ADL5530 offers a 16.5 dB gain in range from DC to 1GHz. When source voltage is 3V and signal frequency is 70MHz, the noise figure of ADL5530 is 3.2dB.

The band pass filter is SAW filter, which has flat pass band, high stop band rejection and transition between pass and stop band is sharp. Those characteristics make SAW filter most suitable for narrow band RF signal. This circuit uses the SAW filter LBN08015 and LBN08020 made by SIPAT, the central frequency is 80MHz and the width of pass band is 4.12MHz and 7.6MHz.

The dynamic range of the incident signal is large, VGAs AD8332 (variable gain amplifier) are used, one AD8332 contain two channels VGA with complementary output. In the circuit, only one port of the complementary output is used, so each AD8332 could offer gain between -10.5 to 37.5 dB. The radio detector part uses LTC5507 RF Power Detector by

Linear Corp. Input signal power of LTC5507 range from -34dBm to 14dBm. A temperature compensated Schottky diode is used for peak detector and buffer amplifier is also integrated in the chip. The signal from LTC5507 is amplified five times by OPAMP, and filtered by 100 kHz LPF.

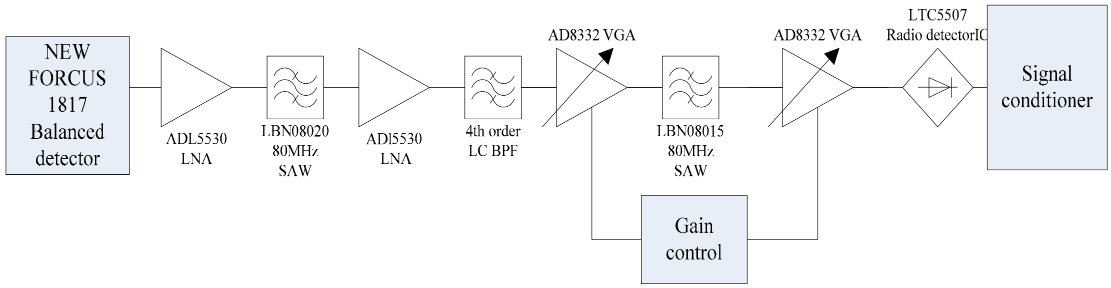

Fig.4 Block diagram of signal conditioning part

3.2 DAQ part

The ADC used in the circuit is AD7687, a 250kSPS 16bit SAR ADC, whose SINAD is 95.5dB and Effective Number of Bits is 15.6bit. When the input reference is 5V, signal span is +5V to -5V. The differential amplifier AD8132 works as ADC driver, changing single end signal into differential signal. Digital signal is sent to computer by USB port.

4 TEST AND CONCLUSION

Fig.5 shows the block diagram of the optical circuit for testing. A 95/5 PM fiber coupler is used split output of laser, 95% power from the laser using as LO, the other 5% is sent to AO frequency shifter then attenuated by fiber attenuator as test signal. The AOM driver has an input port to control the output power of the driver. If the driver strength falls, the diffraction in the AOM would be weakened and the insertion loss of the AOM would increase. In the experiment, the AO frequency shifter also works as a variable attenuator. A fiber polarization controller is inserted to control the polarization state of the test signal.

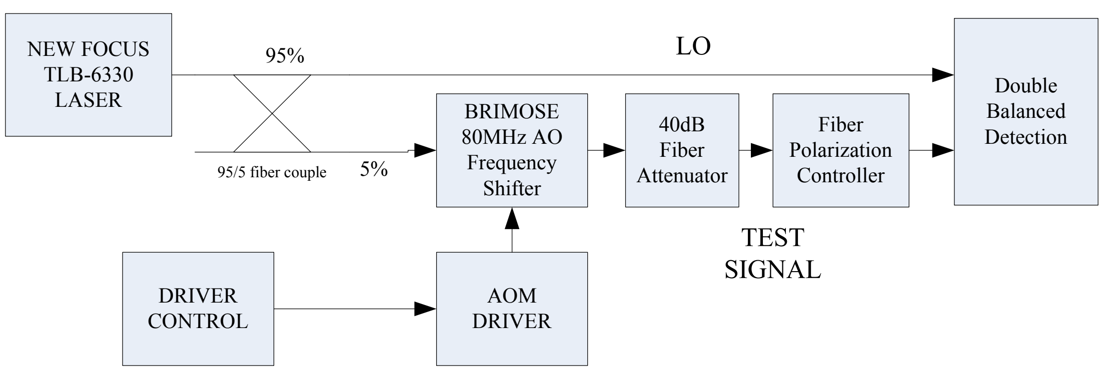

Fig.5 Testing Optical System

Output of the AO frequency shifter contains some of the zero order light of the diffraction, whose frequency isn't changed. If we put AOM in the LO path, not in the test signal path, the leak of the zero order light would disturb the normal detection. The extinction rate of zero order of AOM in our experiment is about 60dB. If the LO is 100μW, the leak zero order signal would be about 50pW, may be much larger than the incident signal.

In this system, wavelength of the laser is 1570.1nm, the responsivity of the PIN photodiode in the balanced detector is

1A/W and the transimpedance gain K is 4×10^4V/A. Assuming the coherent efficiency is 100%, the ideal amplitude of IF signal is $2K\times R\sqrt{(P_{in}P_{loc})}$. The variable attenuation of AOM by different control voltage was measured before the test. The attenuation of the fixed attenuator and the insert loss of other fiber components were also measured. The power of P_{in} could be got by measuring the signal power before the AOM, the LO power was got by measuring the input of the balanced detector.

The balanced photoreceiver used in the experiment has high gain and wide electronic bandwidth, the noise from the photoreceiver is 15mV (RMS). After amplification and filtering, the noise before the radio detector is 50mV (Vpp), the noise of the amplifier is larger than the IF signal, but the power of noise is a constant value, and would be changed to a constant DC value by the LTC5507, even the IF signal is smaller than the noise, its power could be detected. In our experiment, the output of the radio detector was recorded, and the actual IF signal amplitude was got from those data.

We made a simple emulator by two arbitrary function generators and an OPAMP, one as the noise source, the other produced a variable 80MHz sin signal, the OPAMP combined the two signal together to simulate the real signal from the balanced detector. By adjusting the 80MHz sin signal to make the simulative signal produce the same output as the real signal from the detectors, we could get the amplitude of actual IF signal. A comparison was done between the ideal and actual value. The result is shown in fig.6, fig.8 and fig.9; the three figures present the results from different LO power. The experiment result shows a high efficiency (>85%) of the optical system.

Table.1 Average Coherent Degree coefficient @ different LO

LO (μW)	315.6	224.7	161.2
Coherent coefficient h_c	90.1%	87.6%	86.7%

When the LO is 161.2μW and the control voltage of the AOM is a 200Hz sin signal waveform from 0mV to 10mV, the test signal changes between 0.015pW and 0.32pW at frequency of 200Hz, the signal from signal conditioning part is shown in left part of Fig.9, from which a blurred 200Hz signal could be seen. When the control voltage changes to 20mV, which means the signal is between 0.015pW to 1.26pW, output from the circuit is in the right part of Fig.9, in which the 200Hz signal is quite clear. The noise of the radio detector is 0.63mV (RMS). When LO is 315.6μW, 0.63mV represents about incident power of 0.078pW, which means the minimum detection power is 0.078pW when LO is 315.6μW, when LO is 161.2μW, the min detection power should be 0.078*315.6/161.2=0.15pW, which is close to the actual measured value 0.13pW.

In the experiment, some problems of the fiber optical components were found. One of those problems is the impact of the vibration. If the fiber in the system isn't fixed, the vibration of the fiber would change the polarization state of the output light, even the fiber is PM fiber. The vibration introduces the variable pressure on the fiber core, changes the fiber characteristics. The impact of vibration on the PM fiber is much smaller than the SM fiber. All fibers in the optical system, especially the SM fiber, must be fixed well, or the vibration would disturb the polarization state of the output light, which would degrade the precision of the measurement. Another question is the insert loss of the fiber components. PBS and the connector of fiber bring much more insert loss than the fiber, which degrades the sensitivity.

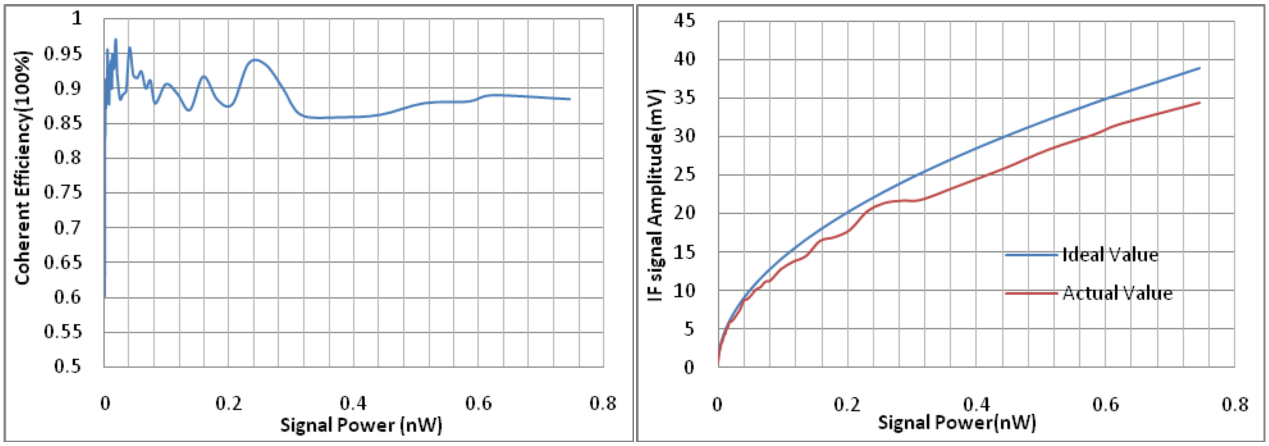

Fig.6 Coherent efficiency and Amplitude of IF signal (LO=315.6μW)

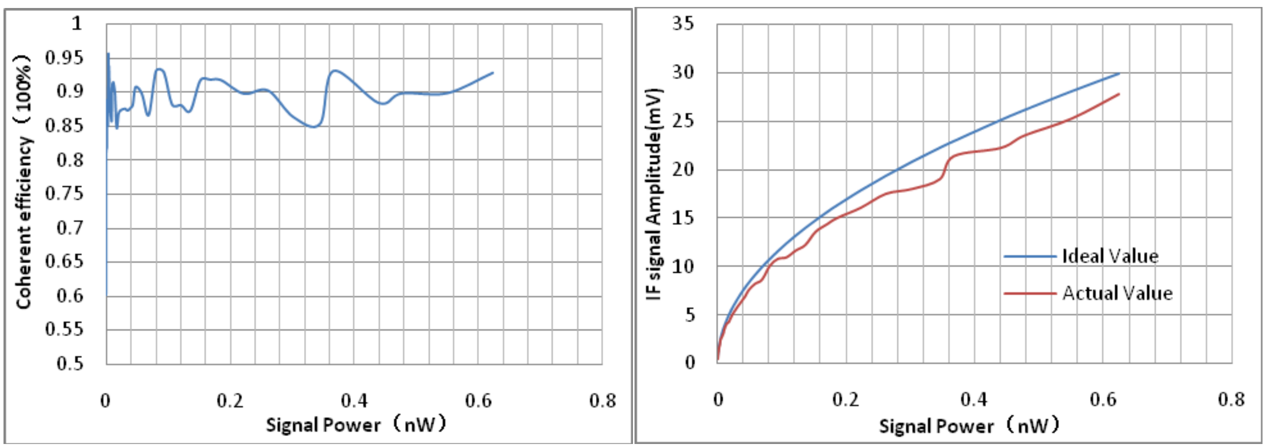

Fig.7 Coherent efficiency and Amplitude of IF signal (LO=224.7μW)

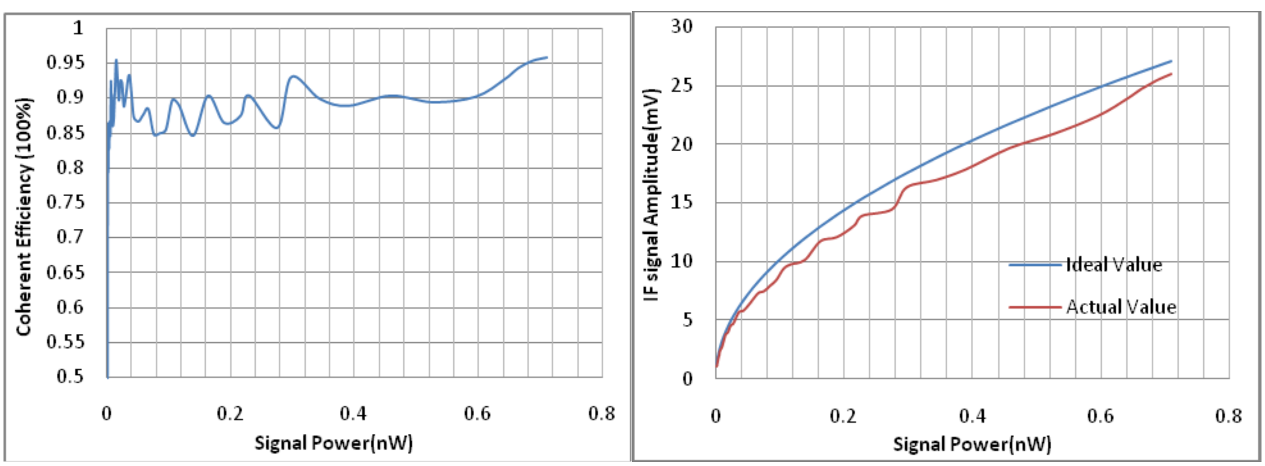

Fig.8 Coherent efficiency and Amplitude of IF signal (LO=161.2μW)

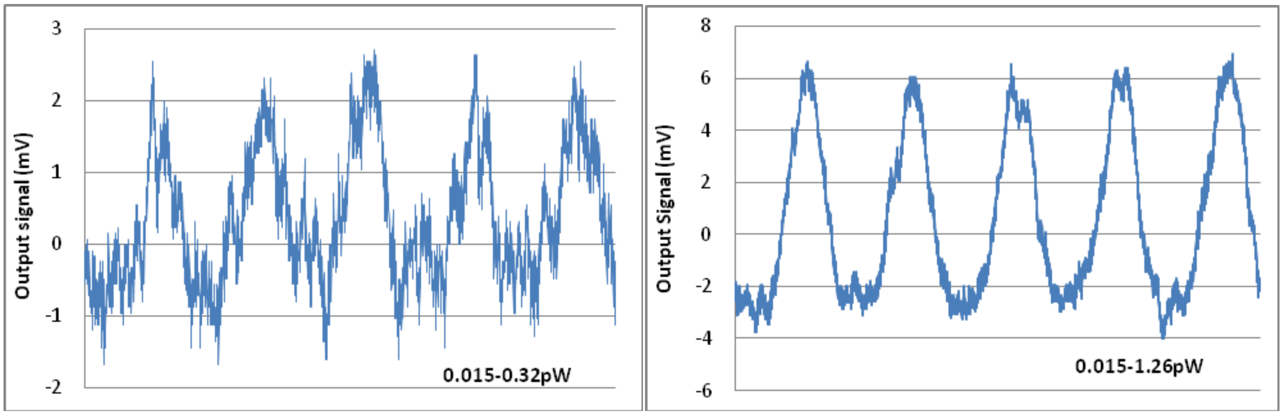

Fig.9 Output of the circuit when test signal changing at 200Hz

5 SUMMARY

The all-fiber double balanced coherent detection system could reach high coherent efficiency (>0.85). The coherent detection show excellent sensibility for the weak signal. Because the measure result depends on the values of LO power and the coherent coefficient, which aren't constant, our coherent detection system couldn't reach high measure accuracy. The experiment result shows an accuracy of about 10%.

6 ACKNOWLEDGMENTS

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