A novel phase noise suppression method for coherent detection by utilizing two adjacent longitudinal modes generated from a supercontinuum multi-wavelength source

D Pan\(^1\), C J Ke\(^1,2,3\), X H Zhu\(^1,2,3\), D M Liu\(^1,2,3\)

\(^1\) College of Optoelectronic Science and Engineering, Huazhong University of Science and Technology, 430074, Wuhan, China
\(^2\) Wuhan National Laboratory for Optoelectronics, 430074, Wuhan, China
\(^3\) National Engineering Laboratory for Next Generation Internet Access System, 430074, Wuhan, China

Abstract. A novel phase noise suppression method for coherent detection is proposed. It uses two adjacent longitudinal modes of a multi-wavelength source, as signal light and coherent light respectively, which are both launched into the optical fiber. And heterodyne synchronous demodulation structure is used in the receiver. The performance of a back-to-back system with 100 Gbit/s NRZ-QPSK utilizing this novel method is investigated by VPI. The simulation results show that phase noise in this coherent detection scheme is suppressed significantly, which is resulted from the correlating phase and fixed frequency spacing of adjacent longitudinal modes.

1. Introduction
In order to cope with the need for ultra high-speed, ultra high-capacity and ultra long-haul optical transmission, coherent detection has attracted significant attentions in research and development during the last several years \(^{[1–7]}\). Coherent receivers could linearly down-convert the whole optical signal to a baseband electrical signal by using heterodyne or homodyne detection, and have the following advantages against direct detection. First, its higher sensitivity makes coherent detection a promising technique for long-haul transmission. Second, the optoelectronic conversion process is linear, so that the whole optical signal information can be postprocessed in the electrical domain. Third, it is applicable to multilevel modulation formats such as multiple phase shift keying (mPSK), multiple quadrature amplitude modulation (mQAM) and orthogonal frequency division multiplexing (OFDM). However, coherent detection is sensitive to the phase noise associated with the transmitter laser and the local oscillator, which is the main impairment for the advanced lightwave systems \(^{[8–9]}\).

Previously, phase noise suppression can be achieved by selecting narrow linewidth laser as local oscillator, or utilizing optical phase-locked loop (OPLL). And phase noise compensation can be realized by digital signal processing (DSP) \(^{[10]}\). Unfortunately, these solutions are relatively high-cost and complex for implementation.

In this paper, a novel method for phase noise suppression in coherent detection is proposed. Two adjacent longitudinal modes from a multi-wavelength source are employed as signal light and coherent light.
light respectively, which are both launched into the optical fiber. And heterodyne coherent detection structure is used to demodulate the signal at the receiver. The simulation shows that this so-called “all-optical phase noise suppression” method would have the potential to replace the aforementioned solutions with simplified receiver structure.

2. System architecture and operation principle

2.1. System architecture

The architecture of the coherent optical communication system adopting the mentioned phase noise suppression techniques is shown in Figure 1. To distinguish from the conventional system which uses a local oscillator at the receiver for coherent detection, we call this NLO (non local oscillator) coherent optical communication system.

![Figure 1. Schematic of NLO coherent optical communication system](image)

In the transmitter, a supercontinuum multi-wavelength optical source is used to generate two wavelength simultaneously, or rather two adjacent longitudinal modes. One is modulated to carry the information as signal, and the other is continuous wave servicing as coherent light. Both of them are launched into optical fiber.

In the receiver, an optical filter is used to fetch out the CW coherence light from the fiber to play the role of local oscillator. Obviously, heterodyne detection is needed to demodulate the signal. By using phase diversities and balanced detection, we can obtain four outputs and detect differential in-phase and quadrature (IQ) components of the signal light. Synchronous demodulation is applied to restore the baseband in the end.

2.2. Operation principle

The AC component of photocurrent in heterodyne detection is given by Eq. (1) [11-12]:

\[
I(t) = 2RP_sP_c \cos(\omega_{IF} t + \phi)
\]

where \( \omega_s \), \( \omega_c \) are the angular frequency of the signal light and coherent light respectively, \( \omega_{IF} = \omega_s - \omega_c \) is the intermediate frequency (IF). \( \phi_s \), \( \phi_c \) are the phase of the signal light and coherent light respectively, \( \phi = \phi_s - \phi_c \) is the phase of IF. \( R \) is the responsivity of photodiode. \( P_s, P_c \) is the optical power of signal light and coherent light respectively.

In coherent detection, phase fluctuations lead to current fluctuations and degrade the SNR. Both the signal phase \( \phi_s \) and the local-oscillator phase \( \phi_c \) should remain relatively stable to avoid the sensitivity degradation. A measure of the duration over which the laser phase remains relatively stable is provided by the coherence time. It is inversely related to the laser linewidth. In conventional system, the IF linewidth \( \Delta \nu \) is actually the sum of the transmitter linewidth \( \Delta \nu_s \) and the local oscillator linewidth \( \Delta \nu_c \), i.e. \( \Delta \nu = \Delta \nu_s + \Delta \nu_c \). This lies in the fact that random variables \( \phi_s \) and \( \phi_c \) fluctuate independently. While in the novel system mentioned in this paper, \( \phi_s \) and \( \phi_c \) fluctuate not independently stemming from the correlation between the two adjacent longitudinal modes of the same optical source. So \( \sigma^2 \), variance of \( \phi \), can be described as the following,
\[ \sigma_{\phi}^2 = \sigma_{S}^2 + \sigma_{L}^2 - 2\rho \sigma_{S} \sigma_{L} \]  

where \( \sigma_{S}^2 \) and \( \sigma_{L}^2 \) are the variance of \( \phi_S \) and \( \phi_L \) respectively, \( \rho \) is the correlation coefficient between \( \phi_S \) and \( \phi_L \). In our method, random variables \( \phi_S \) and \( \phi_L \) are nearly linear correlated, where \( \rho \approx 1 \). This results in the phase noise suppression intrinsically \[13\]. By this means, we can simplify the construction of the coherent receiver remarkably and will not need the OPLL & DSP anymore. Thus the novel “all-optical phase noise suppression” method comes into being.

### 3. Simulation results and discussions

VPI TransmissionMaker\textsuperscript{TM} V8.5 is utilized to evaluate the performance of the aforementioned NLO system, by assuming that single channel 100Gb/s NRZ-QPSK back-to-back transmission. The related simulation parameters are given in table 1. We will emphasize on the performance affected by the linewidth of signal light and coherent light in conventional and NLO system, and analyse the noise limitation further.

**Table 1. Simulation parameters**

| Parameters                              | Values       |
|-----------------------------------------|--------------|
| Average optical power of signal light   | 1 mW         |
| Average optical power of coherent light | 1 mW         |
| Central frequency of signal light       | 193.1 THz    |
| Central frequency of coherent light     | 193.15 THz   |
| Linewidth of longitudinal mode          | 1MHz         |
| Optical Signal Noise Ratio              | 35 dB        |
| Channel spacing of AWG                  | 50 GHz       |
| 3dB bandwidth of AWG                    | 37 GHz       |
| Passband type of AWG                    | Gaussian     |
| Adjacent crosstalk of AWG               | 25 dB        |
| Non-adjacent crosstalk of AWG          | 30 dB        |

#### 3.1. Laser linewidth

Figure 2 shows the simulated symbol error rate (SER) performance of the NLO and conventional system under different laser (or longitudinal mode) linewidths. We can find that the narrower linewidth can lead to more excellent SER performance for both NLO and conventional system. Comparing the inset constellations, whose linewidth and received optical power (ROP) are \(1\text{MHz} \) and -9dBm respectively, it can be seen that the NLO system, which uses two adjacent longitudinal modes from the same optical source to achieve coherent detection, is more effective for obtaining a noiseless accurate phase difference \( \phi \) of IF than the conventional system on the same condition. It also shows that the NLO system can improve the tolerance of laser linewidth for coherent detection from \(100\text{kHz} \) to \(10\text{MHz} \) without any phase estimation techniques which is usually realized by DSP in the conventional system.
3.2. Noise limitation

Figure 3 shows the simulated SER performance of the NLO and conventional system with different optical signal to noise ratio (OSNR) when the laser linewidth for coherent detection is 1MHz. With the increasing of OSNR, SER performance will be enhanced to some extent for both of them, especially in the NLO system. And phase noise would overwhelm the intensity noise in the conventional system when the laser linewidth is about 1MHz order, which causes the SER floor. By the mentioned phase noise suppression method, the NLO system does exhibit better SER performance than the conventional one.

4. Conclusions

This novel method makes a contribution to practical applications of coherent detection in the future developing of optical transmission system. The performance of receiver can be effectively improved, because phase noise is suppressed when the accurate carrier phase estimation based on DSP is not used, so the cost has not increased. Another advantage is that system structure can be simplified. In conventional coherent optical system, it must be provided two sources as transmitter laser and local oscillator. In addition, two wavelengths should be controlled independently. Therefore, it is difficult to construct and control the sources, when wavelength channel number is more than one hundred.
However, in our method, supercontinuum generation is an effective way of obtaining more than one hundred optical longitudinal modes and the devices are easier to control.

Acknowledgement
This work was supported by the National Basic Research Program of China (No.2010CB328302)

References
[1] Rakefet W, Moshe N, Reinhold N and Isaac S 2009. ECOC (Vienna: Nexus Media Limited) Paper 2.3.3.
[2] Sano A, Yamada E and Masuda H 2008 ECOC (Brussels: IBBT) Th.3.E.1
[3] Winzer P J, Gnauck A H and Doerr C R 2010. J. Lightwave Technol. 2010, 28 547
[4] Bertran-Pardo O, Renaudier J and Charlet G 2009 ECOC (Vienna: Nexus Media Limited) 2009. Paper 9.4.1
[5] Yu J J, Zhou X and Huang M F 2008 ECOC (Brussels: IBBT) Th.3.E.2
[6] Jansen S L, Morita I and Tanaka H 2008 OFC/NFOEC. (San Diego: OSA) OMU3
[7] Ammon Y 2004 Optical Electronics in Modern Communication (Beijing: Publishing House of Electronics Industry) p 302
[8] Franz J H and Jain V K 2002 Optical Comunications Components and Systems (Beijing: Publishing House of Electronics Industry) p 317
[9] Kazovsky L G, Benedetto S and Willner A 1999 Optical Fiber Communication Systems (Beijing: Publishing House of Electronics Industry) p 223
[10] Seb J S 2008 Opt. Express 16 804
[11] Agrawal G P 2002 Fiber-optic Communication Systems (New York: John Wiley & Sons, Inc.) p 480
[12] Kazuro K 2008 Coherent optical communication systems Optical Fiber Telecommunications V B (System and Networks) ed Ivan P. Kaminow, Tingye Li and Alan E. Willner (New York: Academic Press) chapter 3 pp 95–129
[13] Zhu N H, Li W and Wang L X 2009 J. Quant. Electron. 45 514