Modeling of Optical Carrier Recovery using Four Wave Mixing Technique for Binary Phase Shift Keying Systems

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***Abstract*—Modern communication networks uses optical fibre extensively. The transport networks are upgrading its capacity continuously to provide the bandwidth requirement of the customer requirements. To provide such an increase in bandwidth, the transmission networks are moving from Amplitude Shift Keying modulation methods to Phase Shift Keying methods. In phase shift keying systems, data reception and regeneration required phase synchronization. This requires original optical carrier phase information. In this paper, we report a model for optical carrier recovery for optical synchronization of a Binary Phase Shift Keying input by exploiting Four Wave Mixing in Highly Non-Linear Fibers. The noise influence from the signal laser for the recovered carrier was analyzed.**

Keywords—Optical Fiber Communications, Four Wave Mixing, Binary Phase Shift Keying, Linewidth and Signal to Noise Ratio.

I. INTRODUCTION

The field of Optical Communications has gained rapid development throughout the past few decade [1], [2]. The network capacities have moved from 40 Gbps to 100 Gbps data rates per single channel [2]. Therefore, it is essential to cater for these developments, the modulation schemes should be shifted from amplitude-shift-keying (ASK) to phase shift keying (PSK) schemes, such as Binary Phase Shift Keying (BPSK), Differential Phase Shift Keying (DPSK), etc [3]. Moreover, most of the recently deployed high capacity systems are operating on phase modulation schemes [3], [4]. Because of this reasons the methods used for signal processing in amplitude modulation schemes will be no longer effective. Therefore, new schemes for signal processing should be researched. In phase modulation schemes, the carrier phase information from the incoming data should be extracted. However, in most of the PSK modulation schemes, a strong carrier is not available after the modulation compared to ASK modulaion [5], [6]. Therefore, carrier recovery at the receiver-circuitry plays a major role when it comes to accurate and efficient signal reception and processing. Recovery of the original carrier from the incoming signal for data regeneration, synchronization and operation of optical receivers require original carrier phase information. This research intends to show an attempt of carrier recovery. The relevant applications are phase synchronization for phase regeneration [3], [4], phase sensitive amplification [3], [7] and homodyne receivers [8], [9].

Optical carrier recovery using various other methods have been experimented [5], [10], [11]. The optical carrier recovery using Four Wave Mixing (FWM) in a Highly Non-Linear Fibers (HNLF) was earlier experimentally demonstrated by R. Weerasuriya, et al [6]. However, in that paper a more detailed analysis of noise influence was not carried out. In this research, a similar model for optical carrier recovery using a binary phase shift keying signal was modeled. The simulation model was tested for carrier recovery and the master laser noise influence on the recovered carrier was analyzed.

II. PRINCIPLE OF OPERATION

The optical carrier recovery presented in this paper was based on the Four Wave Mixing. FWM is a nonlinear phenomenon that occurs in a non-linear medium at high optical powers. Four wave mixing occurs due to the third order nonlinear susceptibility which is a result of nonlinear contribution to refractive index in silica fibers [12]. When three optical signals with adequate power are propagating in a fiber, they excite the non-linearity. Because of the non-linearity the signal are mixed with each other resulting in new frequencies called idlers as shown in Figure 1. Two types of four wave mixing methods have been identified in literature [11], [13]:

- Non-degenerate
- Degenerate

In degenerate FWM, only two signals are mixed together which results symmetric idlers. Similarly in non-degenerate FWM, the mixing happens between three signals resulting in idler signals with lower intensities [14], [15].

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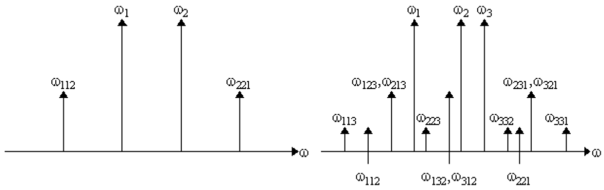

Fig.1 Four wave mixing output [16]

The electric field variation, angular frequencies and the phase information of the new idlers are given from the following equations, where E_s, E_p are signal and pump field strengths, ω_s, ω_p are signal and pump angular frequencies and Φ_s, Φ_p are signal and pump phases respectively [6]:

$$E_{i1} = E_s^2 . E_p^* . e^{i[(2\omega_s - \omega_p) - (2\phi_s - \phi_p)]} \qquad (1)$$

$$E_{i1} = E_s^2 . E_p^* . e^{i[(2\omega_s - \omega_p) - (2\phi_s - \phi_p)]} \qquad (2)$$

$$\omega_{i1} = (2\omega_s - \omega_p) \qquad (3)$$

$$\omega_{i2} = (2\omega_p - \omega_s) \qquad (4)$$

$$\phi_{i1} = (2\phi_s - \phi_p) \qquad (5)$$

$$\phi_{i2} = (2\phi_p - \phi_s) \qquad (6)$$

If we consider equation 5, assuming the pump phase is “0” and the BPSK data phases are 0 & π, the phase of the incoming BPSK data signal has been erased for both phases. This is illustrated in table 1.

Table1: Idler phases for different data phases

Pump Phase	Data Phase	Idler 1 [eq. (5)] Phase	Idler 2 [eq. (6)] Phase
0	0	0	0
0	π	2π = 0	-π

Therefore, it can be concluded that the original phase modulation has been stripped from the idler 1 and the carrier phase has been preserved during the transformation.

III. Simulation Model

A BPSK modulated signal was produced with a random incoming data sequence. This BPSK signal (194THz) and a continuous wave laser signal was coupled, amplified and launched into a nonlinear media to participate in Four Wave Mixing process. Pseudo random binary sequence length used was 1024 (PRBS10). The experimental setup of the simulation model is shown in Fig. 2

The output of the nonlinear media was analyzed in frequency domain, by plotting the spectrum diagrams. The output spectrum showed four signals, the input BPSK, pump and the new generated two idlers. One idler has a strong carrier present. This gave the evidence that one of the idler has the phase information of the data signal laser and further confirming the recovery of the carrier. Furthermore the resulting four-wave mixing output was analyzed in time domain. The time domain plots were taken for original signal laser, BPSK signal and the recovered idler 1 to verify the phase erasure.

Finally some colored noise was added at the signal laser and observed the linewidth. For each case, the four wave mixing process lead to carrier recovery and the analysis is discussed in the results.

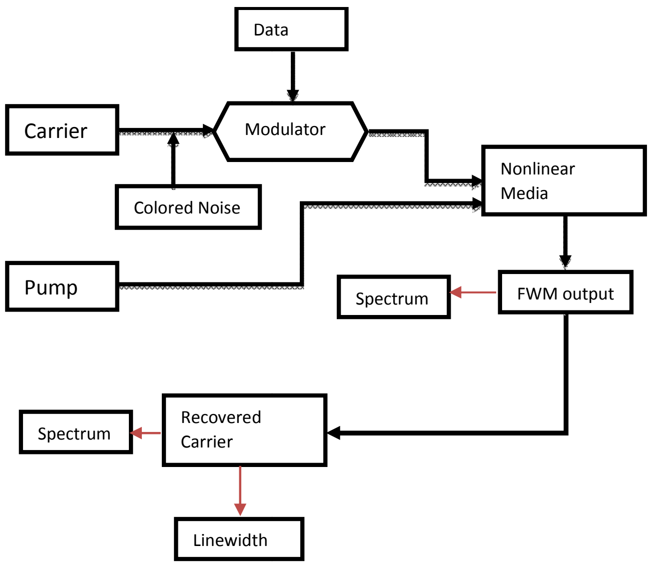

Fig. 2. Simulation Model for optical carrier recovery

IV. Results

The output spectrum of the highly nonlinear fiber was shown in Fig. 3 after the four wave mixing process. It has confirmed the FWM process showing the newly generated idlers.

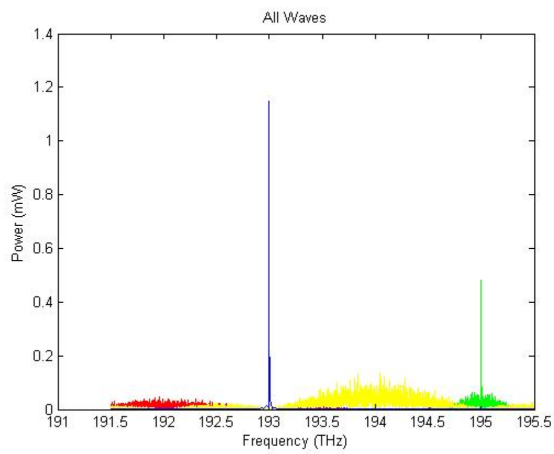

Fig. 3 four wave mixing output

The pump, BPSK, idler 1 and idler 2 are shown in blue, yellow, green and red respectively. According to the equations 5 and the table 1, it was evident that the idler 1 is the recovered carrier.

In Fig. 4, an enlarged figure of the idler 1 is shown and it further confirmed that the modulation was stripped off from the incoming data signal and the phase information of the data laser was transferred to the idler1.

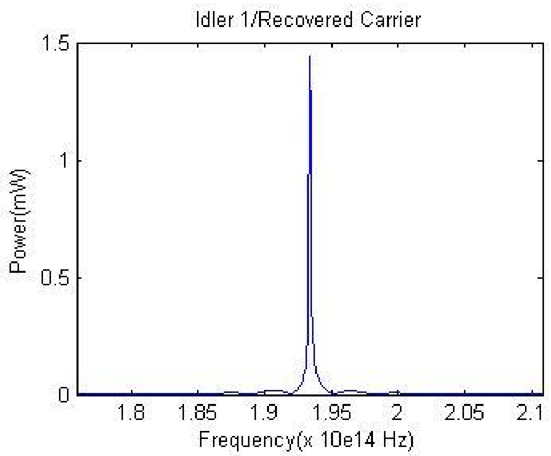

Fig.4. Recovered Carrier

In order to further verify that the recovered idler has erased the phase information the time domain analysis was carried out. For this analysis the time domain variation of the outputs of the original signal laser, the BPSK modulated signal and the recovered carrier were checked (Fig. 5). In the top inset of Fig. 5, the signal laser variation was shown. It follows a clear, CW laser pattern. However, in the middle inset of Fig.5 it can be seen the phase jumps due to BPSK modulation. The bottom inset shows the time domain signal of the recovered carrier and it has lost those phase jump information. Therefore, it can be conclude that the phase erasure has taken place due to the four wave mixing process of our simulated model. Therefore, it confirms that the phase of the recovered carrier was erased and the phase of the original carrier was obtained.

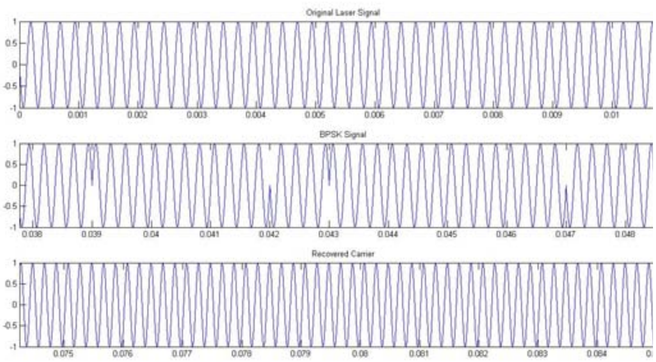

Fig. 5. Time domain signal variation (top: Original signal laser, middle: BPSK signal, bottom: recovered idler 1)

After confirmation of the carrier recovery, the noise analysis was carried out. To perform noise analysis, controlled amounts of colored noise were added to the signal laser and the full-width half maximum (FWHM) linewidth of the recovered carrier was measured. For each noise value, the spectrum and the linewidth was obtained. As it can be seen from the Fig. 6 to 10 and Table 2, it can be observed that the linewidth of the recovered carrier was increased when there is more noise in the master laser. Furthermore, we can assume that the in-band noise addition due to transmission also degraded the recovered linewidth as it degraded the Optical Signal to Noise Ratio (OSNR) of the signal. The system was breakdown with a larger linewidth after the OSNR was degraded to 10.9 dB. It can be also confirmed by comparing the Fig. 9, Fig. 10 and Fig. 11. In Fig. 10, the recovered carrier has diminished and the sudden linewidth increment was shown in Fig. 11. However, for a practical system the system breakdown OSNR will be higher, as it may encounter various noise in the laser as well as during the transmission.

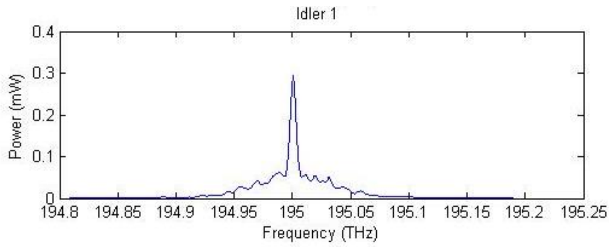

Fig. 6. Spectrum of idler 1(noise power = 0.1 mW and the signal power = 5 mW).

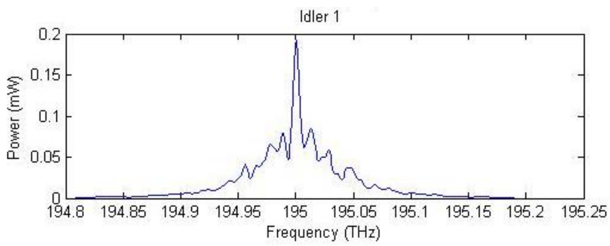

Fig. 7. Spectrum of idler 1(noise power = 0.2 mW and the signal power = 5 mW).

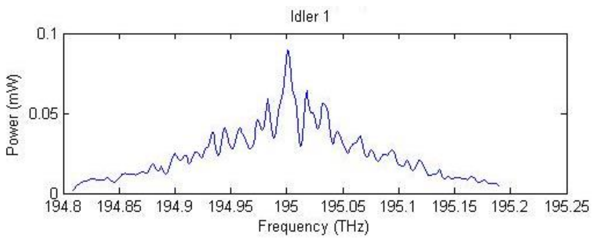

Fig. 8. Spectrum of idler 1(noise power = 0.3 mW and the signal power = 5 mW).

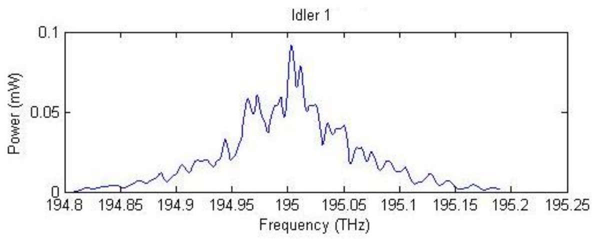

Fig. 9. Spectrum of idler 1(noise power = 0.4 mW and the signal power = 5 mW).

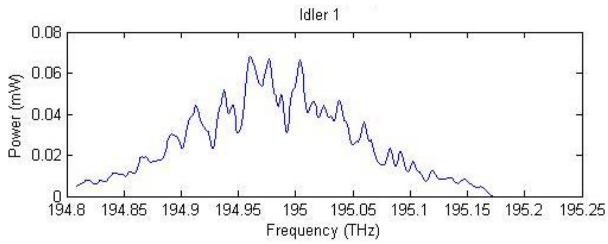

Fig. 10. Spectrum of idler 1(noise power = 0.5 mW and the signal power = 5 mW).

Table 2: Input noise power vs linewidth

Input Noise Power (mW)	**Calculated OSNR (dB)**	**Linewidth (MHz)**
0.1	16.9	6
0.2	13.9	19
0.3	12.2	50
0.4	10.9	66
0.5	10	163

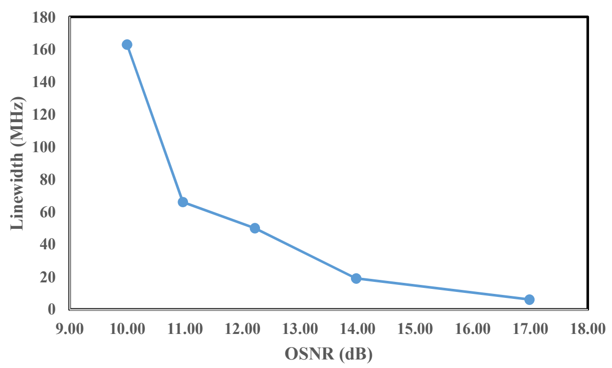

Fig. 11. Measured Linewidth vs. OSNR.

V. CONCLUSIONS

In conclusion, we have proved that the simulation model for the optical carrier recovery using FWM in HNLF is successful. Our results include an idler phase-locked with the initial carrier which proves the carrier is recovered. Furthermore, we have investigated the colored noise tolerance which acts as in-band noise for the system. Colored noise added to the system with an intensity of a few microwatts incorporated linewidth to the recovered carrier. As expected, the linewidth and the Idler OSNR were degraded with more additive noise power.

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