Duobinary Modulation Format and Unequal Channel Spacing Integration to Suppress Four-Wave Mixing Crosstalk in WDM Systems

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ABSTRACT

This paper presents a study of the effectiveness of integrating unequal channel spacing and duobinary modulation format as a good alternative of conventional non-return to zero (NRZ) modulation format to further suppress four-wave mixing (FWM) crosstalk in a four 10-Gbps channels wavelength division multiplexing (WDM) system. The study is conducted using VPI Transmission Maker Simulator. The results show that duobinary modulation has a better performance in suppressing FWM than conventional NRZ, and that using unequal spacing with duobinary modulation further improves the suppression of FWM products in WDM systems.

***Index Terms*—** Four-wave mixing, duobinary modulation dispersion shifted fibers, channel spacing, and wavelength division multiplexing systems.

I. INTRODUCTION

For two decades, researchers have been developing different methods and techniques to reduce the effect of FWM crosstalk in high speed/long haul optical communication systems. This nonlinear effect is considered the main cause for crosstalk degradation in WDM systems employing dispersion-shifted fibers (DSFs) [1]. Different methods like unequal channel spacing, dispersion management, and advanced modulation techniques have been proposed as a solution of this impairment [2]-[7].

In a previous work, the effectiveness of using unequal channel spacing algorithm in suppressing FWM waves in WDM systems, through a comparison of the transmission of four 10-Gbps channels over 50 km of repeaterless DSF between equal and unequal channel spacing schemes using conventional non-return to zero (NRZ) modulation format was reported [7]. The results showed that using an unequal channel spacing scheme with a minimum frequency spacing (50 GHz) results in greatly reducing the generation of FWM products at the channel frequencies and improving the overall performance of the system.

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In this paper, a study of the effectiveness of integrating unequal channel spacing with duobinary modulation format as an advanced modulation technique, which has been used in many researches as a good alternative of the conventional NRZ, is reported.

II. MODEL AND SIMULATION

To investigate the effectiveness of the proposed model, first, the simulation results of the duobinary modulation for both equal and unequal channel spacing are presented. Then, the measured FWM power when channel 3 is turned off is compared for both equal and unequal spacing duobinary. Finally, all the results obtained from both NRZ modulation and duobinary modulation are compared to investigate whether this integration will further improve the system performance.

The channels allocation algorithm used here is the same algorithm used in the previous work [7], where four 10-Gbps channels are transmitted over 50 km repeaterless DSF. As mentioned, duobinary modulation format will be used for both equal and unequal channel spacing instead of NRZ modulation, with a minimum channel spacing Δf_c = 50 GHz to compare their performance. The slot width Δf is 25 GHz.

In order to illustrate the effectiveness of the suggested integration in suppressing FWM waves, the VPI model remains the same like that of [7], except in replacing the NRZ transmitters with duobinary transmitters. The system is simulated with the experimental setup block diagram shown in Fig. 1.

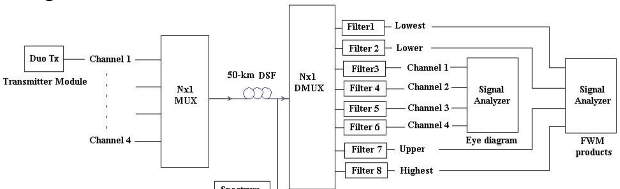


Figure 1 Block diagram of the used system.

It consists of 4 channels 2 mW each, modulated by Mach-Zehnder modulator. A 50 km of near-zero DSF with a fiber loss of 0.2 dB/km and a dispersion of 0.2 ps/nm·km is used.

The zero dispersion frequency f_o = 193.1 THz. The assigned frequencies of the four channels are shown in Fig. 2(a) with equal channel separations of 50 GHz. The channels are assigned the frequencies 193.025, 193.075, 193.125, and 193.175 THz. The total equal bandwidth is 150 GHz. Figure 2(b) shows the assigned frequencies with the unequal channel spacing. The minimum channel spacing is Δf_c = 50 GHz. The channels are assigned the frequencies 192.9625, 193.0625, 193.1375, and 193.1875 THz. The channel separations from left to right are, respectively, 100, 75 and 50 GHz. The total unequal bandwidth is 225 GHz. The minimum number of slots between any two channels is n = 2. It is clear that the bandwidth expansion is 1.5.

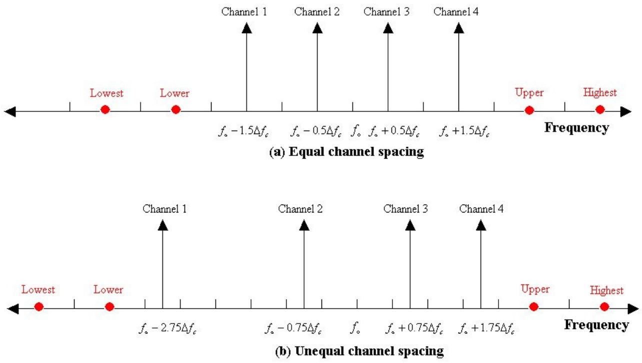
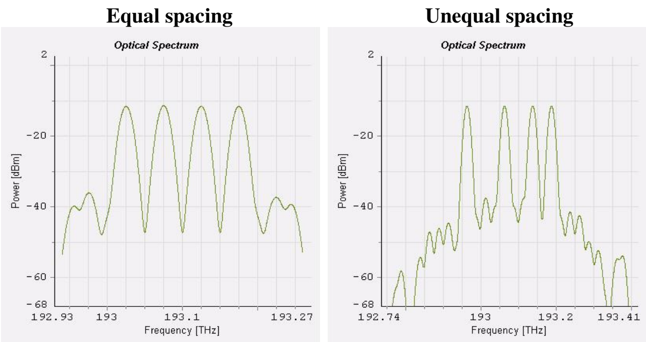


Figure 2 Schematic of the assigned frequencies for the four transmitted channels with (a) equal channel spacing and (b) unequal channel spacing.

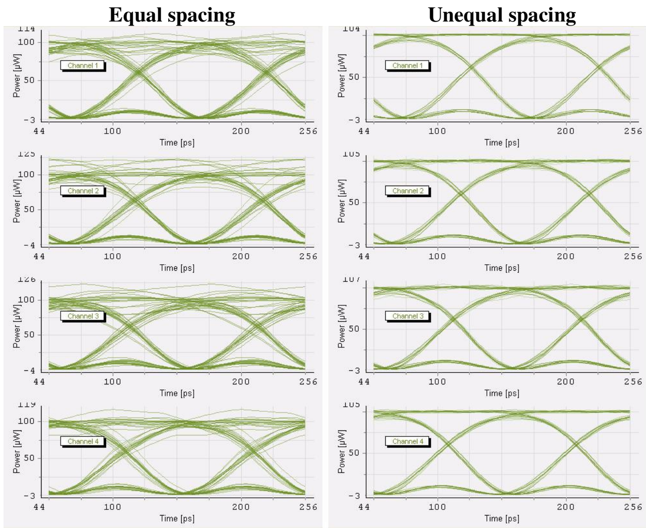
Figure 3 shows a comparison of the output spectrum of duobinary modulation at the output of the 50 km DSF with a zero dispersion frequency f_o = 193.1 THz when four 2 mW channels are launched at the input of the fiber for both equal channel spacing, Fig. 3(a), and unequal channel spacing, Fig. 3(b). It can be seen that, the FWM waves in duobinary modulation for unequal channel spacing are generated in the spaces between the channels and outside the received bandwidth. Moreover, the power of the FWM waves is greatly depleted in the unequal channel spacing compared to that of the equal spacing.



(a) **(b)**

Figure 3 Comparison of the fiber output spectrum of duobinary modulation for (a) equal channel spacing and (b) unequal channel spacing. Both at the output of 50 km DSF (D=0.2 ps/nm.km) for four 10 Gbps channels with 2 mW launched power each.

The eye diagram of the duobinary modulation of the received four channels is shown in Fig. 4. It shows a distortion, to some extent, with the equal channel spacing shown in Fig. 4(a) due to the FWM crosstalk caused by the interference between the transmitted channels and the generated FWM waves at the channel frequency. Figure 4(b) shows the improvement in the eye diagram with the unequal channel spacing. As in NRZ modulation [7], this is due to the generation of FWM products outside the channel bandwidth and in the spaces between the channels.



(a) **(b)**

Figure 4 Eye diagram of the four channels after 50 km transmission for (a) equal channel spacing each (degraded) and (b) unequal channel spacing (improved).

Figure 5 displays the power depletion of the generated FWM products as they travel along the optical fiber. The lines are the measured FWM products outside the channel frequency bandwidth.

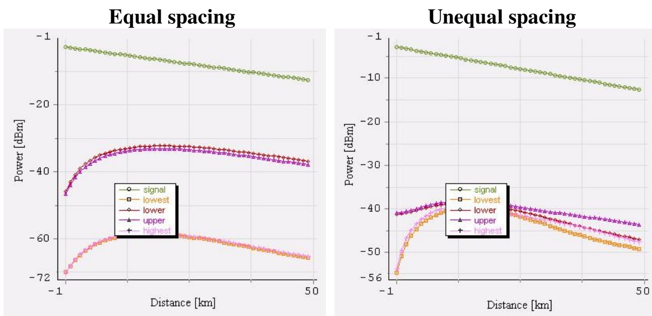


Figure 5 FWM products versus transmission distance of duobinary modulation for equal and unequal channel spacing.

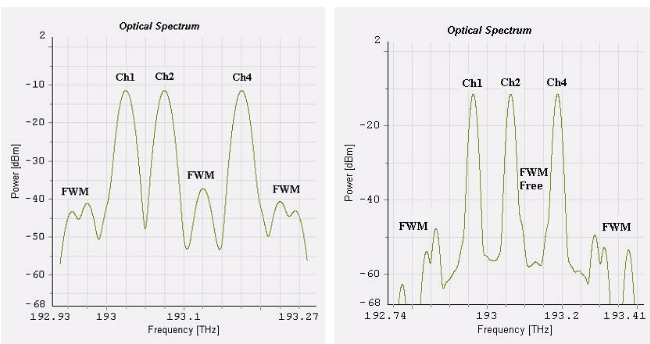
The line with circles (labeled signal) is the measured power at channel 3 at frequencies f_o+0.5Δf_c and f_o+0.75Δf_c, for equal and unequal channel spacing, respectively. The line with crosses (labeled highest) is the FWM products measured at f_o+3.5Δf_c. The line with triangles (labeled upper) is the FWM products measured at f_o+2.5Δf_c. The line with rhombuses (labeled lower) is the FWM products measured at f_o-3.5Δf_c. The line with squares (labeled lowest) is the FWM products measured at f_o-4.5Δf_c. Δf_c = 50 GHz is the minimum channel spacing.

Comparing the FWM products of duobinary modulation generated with equal channel spacing, and that generated with unequal channel spacing, one can notice that, the FWM power at location "Upper" is decreased by 5 dBm for unequal channel spacing compared to equal spacing**.** The FWM power at location "Lowest" is increased by 16 dBm for unequal channel spacing compared to equal spacing.

It should be noted that although the increment of 16 dBm at location "Lowest" is greater than the decrement of 5 dBm at location "Upper", the FWM power at location "lowest" in the equal spacing is very small (- 65 dBm), and hence a 16 dBm increment in the power will not have a great influence on the FWM power in the unequal channel spacing. It is still going to be very small (- 49 dBm) as well. This happens for the same reason as mentioned in our previous work [7]. In equal channel spacing, all mixing products are located on slots occupied by the channels, generating maximum interference, and that on some channels (near the center), there exists the majority of FWM waves. While in unequal channel spacing, mixing products are all evenly distributed on the slots between the channels.

III. FWM PRODUCTS AT CHANNEL 3

In the previous work [7], in order to measure the FWM power at channel 3, the simulation was conducted with channel 3 turned off, and the FWM products generated by the other transmitted channels were measured at channel 3. Now, in order to investigate the effectiveness of integrating unequal channel spacing and duobinary modulation format in suppressing FWM waves in WDM systems, all the steps mentioned above will be repeated and the FWM products power is measured at channel 3 and compared for both equal and unequal channel spacing, Fig. 6.



(a) (b)

Figure 6 Fiber output spectrum of duobinary modulation for (a) equal channel spacing (b) unequal channel spacing.

From Fig. 6, it can be seen that, in duobinary modulation for the equal spacing, there are FWM waves generated at channel 3. On the other hand, for the unequal spacing, channel 3 is free of FWM products and the FWM products generated outside the received bandwidth are depleted.

Figure 7 shows a comparison of the FWM products versus the transmission distance generated for both equal and unequal channel spacing with duobinary modulation. It is clear that, at channel 3, the FWM products (the green line with small circles) are greatly depleted in the unequal channel spacing. This means that for the equal spacing with channel 3 turned off, the other transmitted channels generate FWM products at channel 3 but for the unequal spacing, channel 3 is free of FWM products.

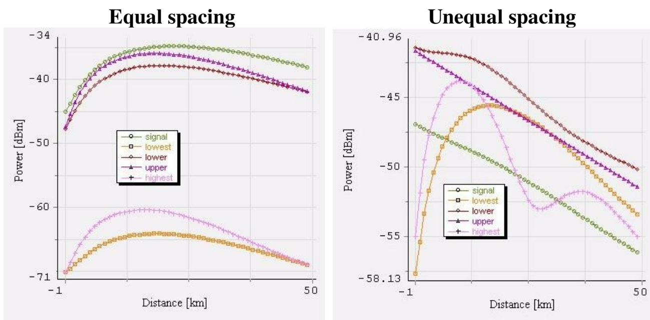


Figure 7 FWM products versus the transmission distance for equal channel spacing, and unequal channel spacing, both with channel 3 turned off.

Figure 8 summarizes the results of duobinary modulation obtained in section III. It compares the FWM products power measured at channel 3 for both equal and unequal channel spacing.

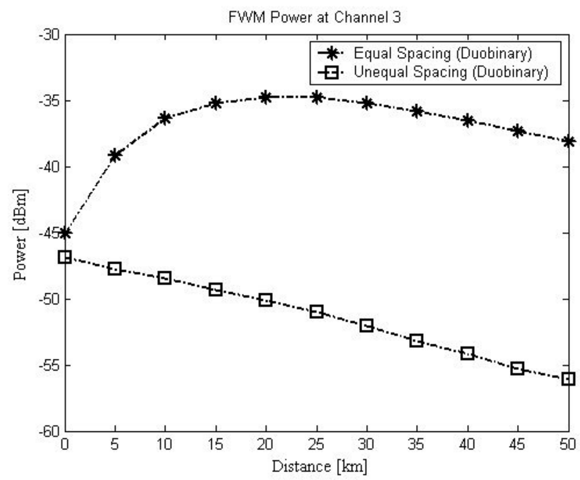


Figure 8 FWM products power measured at channel 3 for both equal and unequal spacing for duobinary modulation.

It is clear that, the amount of reduction is 18 dBm in FWM products power measured at channel 3 (in equal channel spacing after a transmission of 50 km is –38 dBm compared to –56 dBm in unequal spacing).

In the following Section, the obtained simulation results for both NRZ [7], and duobinary modulation format which is used in this work are summarized and compared for both equal and unequal channel spacing.

IV. SUMMARY OF RESULTS

Figure 9 shows a comparison of the measured FWM products power at channel 3 when channel 3 is turned off. It can be seen that the measured FWM power in NRZ equal spacing is the highest generated FWM power, while duobinary unequal spacing is the lowest generated FWM power, with even less FWM power than unequal spacing NRZ.

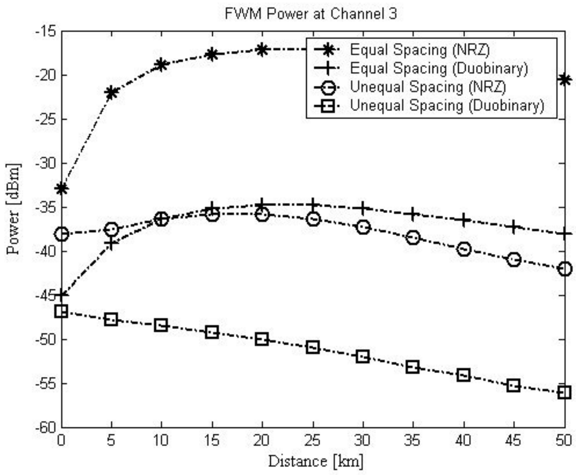


Figure 9 FWM products power measured at channel 3 for both equal and unequal spacing in both NRZ and duobinary modulations.

It is clear that, using unequal channel spacing with conventional NRZ modulation format will give better results than both equal spacing NRZ, and equal spacing duobinary modulation formats. Moreover, integrating unequal spacing with duobinary modulation as an advanced modulation format will further improve the suppression of FWM products power by 14 dBm compared to unequal spacing NRZ, to finally reach a minimum FWM products power of –56 dBm. One would expect this value to increase relatively when all channels are on, due to the more FWM waves being generated.

The reduction of the spectral width of the optical duobinary signal is the reason for its better dispersion tolerance compared to NRZ signals and enables an improved spectral efficiency in WDM systems. For this, we propose a model for integrating both unequal channel spacing and duobinary modulation format to further suppress the generation of FWM waves in WDM systems.

It is worth noting that, the nonlinear refractive index, n_2, in dispersion-shifted fibers (DSFs) is 2.6×10^{-20} m^2/W, while in this study we used a worst value of 3.2×10^{-20} m^2/W. So, one can expect better results than the previously obtained when $n_2 = 2.6\times10^{-20}$ m^2/W is used.

V. CONCLUSION

In this paper, a study of the effectiveness of integrating unequal channel spacing and duobinary modulation format, as a good alternative of conventional NRZ in suppressing FWM waves in WDM systems is reported. It has been demonstrated that the merge is possible, and using unequal channel spacing with duobinary modulation format gives better results than both unequal spacing NRZ and equal spacing duobinary modulation formats. Moreover, this integration further improves the suppression of FWM products power by 14 dBm compared to unequal spacing NRZ, to finally reach a minimum of –56 dBm for the FWM products power. This value would relatively increase when all channels are transmitted. We should note that, using unequal spacing is on the expense of bandwidth expansion but still, the integration of the two techniques remains an appealed solution to FWM waves impairments in WDM systems.

VI. REFERENCES

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