# 行政院國家科學委員會專題研究計畫　成果報告

## 改善光纖非線性效應對超寬頻波長多工光通信系統作用之研究

計畫類別：個別型計畫
計畫編號：NSC92-2215-E-216-003-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：中華大學電機工程研究所

計畫主持人：溫盛發

報告類型：精簡報告

處理方式：本計畫可公開查詢

中　華　民　國 93 年 10 月 13 日

# 行政院國家科學委員會專題研究計畫成果報告

## 改善光纖非線性效應對超寬頻波長多工光通信系統作用之研究

## Improvement of the effects of fiber nonlinearity on ultra-wide band WDM optical communication system

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### 一、中文摘要

本計劃研究在有色散管理的長距離波長多工光通信系統中使用幾種不同的預先瞬時頻率調變信號以改善光纖非線性效應的影響。我們考慮三個波段：色散過分補償(1535nm)、補償良好(1550nm)、與補償不足(1585nm)。發現不同補償狀況可以用不同預先瞬時頻率調變形式的信號改善系統品質。

**關鍵詞**：光通信、預先瞬時頻率調變、歸零預先瞬時頻率調變、光纖色散補償。

### Abstract

This project studied the dispersion-managed long-haul WDM optical communication systems using several different chirped signals to improve the effects of fiber nonlinearities on system performance. Three wavelength bands of highly over dispersion compensation (1535-nm band), well dispersion compensation (1550-nm band), and highly under dispersion compensation (1585-nm band) are considered. It is found the use of proper chirped signals for each band improves system performance.

**Keywords**: optical communication, wavelength division multiplexing, dispersion compensation, fiber nonlinearities, chirped signal.

### 二、緣由與目的

Pre-chirping of signal pulse can be used to compensate for fiber dispersion [1]. On the contrary, pre-chirping can be used to enhance pulse broadening for the case of high residual dispersion so that the effects of fiber nonlinearities can be reduced [2]. Chirped RZ (CRZ) signal and Chirped NRZ (CNRZ) signal have been considered to further improve system performances [1-3]. Cosine phase modulation can be applied to the signals at transmitter and results in the frequency chirping of sine function. We consider the cases of the phase modulation frequency $f_p$ equal to bit rate $B$ and half the bit rate $0.5B$. With $f_p = B$, every signal bit is pre-chirped the same. RZ and NRZ signals with the pre-chirping of $f_p = B$ are called CRZ and CNRZ, respectively, to distinguish from the case with $f_p = 0.5B$ in which the neighboring bits are pre-chirped with opposite sign and such signals are called alternately chirped (AC) signals. AC-RZ and AC-NRZ signals have been considered [4-6]. The performance with AC-RZ signal has not yet been clearly investigated. We call CRZ and CNRZ signals as non-alternate chirping (NAC) signals. In this paper, we compare the performance of ultra-long and high-speed WDM systems with the pre-chirped signals, which are CRZ, AC-RZ, CNRZ, and AC-NRZ signals. The impacts of fiber nonlinearities on the pre-chirped signals are studied.

## 三、結果與討論

10-*Gb/s* bit rate and 9,000-*km* transmission distance is considered. Non-zero dispersion shifted fiber (NZDSF) is used as transmission fiber. At 1550 nm, its dispersion parameter and dispersion slopes are 3.5 ps/km/nm and 0.085 ps/km/nm$^2$ respectively. Fiber loss is taken as 0.22dB/km and is periodically compensated by the optical amplifiers of 5 dB noise figure, where the amplifier spacing is 50 km. Large effective area fiber of 100μm$^2$ is assumed to reduce fiber nonlinearities. Fiber dispersion is compensated by the dispersion compensation fiber (DCF) of –100-ps/km/nm dispersion parameter at 1550 nm. We use symmetric dispersion map for the considered system with a period of $L_c$= 500 km. Over dispersion compensation ratio is defined as $\delta = -(DL_c+D_{dcf}L_{dcf})/DL_c$, where $D$ and $D_{dcf}$ are the dispersion parameters of transmission fiber and DCF, respectively; $L_{dcf}$ is the length of the DCF used in a compensation period. For the case of $\delta>0$, fiber dispersion is over compensated. We take $\delta$= 0.01 at 1550 nm so that $L_{dcf}$ = 17.68 km. Fig. 1 shows path-averaged dispersion $D_{avg}$ and over dispersion compensation ratio $\delta$ versus wavelength. We respectively investigate the characteristics of WDM signals in the three wavelength bands: 1535nm, 1550nm, and 1585 nm. The WDM system of eight signal channels for each wavelength band is considered. The carrier frequencies of the WDM signals follow ITU grid. The eight channels in a wavelength band are the same pre-chirped. System performance is evaluated by $Q$ factor. At receiver, PDC is used to tailor the received pulse shapes so that $Q$ factor of each channel is optimized respectively. Fig. 2 shows the spectra of two neighboring signal pulses for the CRZ, AC-RZ, CNRZ, and AC-NRZ signals with the maximum chirping frequency $f_{pm}$ = 25 GHz and the average signal power $P_{avg}$ = 1.0 mW. It is noticed that the carrier frequencies of neighboring pulses are differently shifted. In Fig. 2, the spectrum of an AC signal pulse lies in either low frequency or high frequency part of the frequency band that depends on the pulse is negatively pre-chirped or positively pre-chirped. For all the four signal formats, as the pre-chirping broadens signal spectral width, spectra of neighboring channels overlap when $f_{pm}$ is about 30GHz for the WDM system with 100GHz channel separation.

Pre-chirping can be used to compensate for fiber dispersion. In the well dispersion compensated wavelength band (1550 nm), proper pre-chirping help to maintain or compress signal pulse. We call the signal propagation with such characteristics as the pulse transmission mode (PTM). For the ultra-long system with high residual fiber dispersion, pre-chirping usually is not able to maintain pulse shape but enhances pulse broadening instead. For the other two wavelength bands (1535 nm and 1585 nm), pre-chirping enhances pulse broadening and pulses are seriously broadened. We call the signal propagation with such characteristics as the dispersive transmission mode (DTM). This section considers the case with only Kerr nonlinearity which may compress or enhance pulse broadening through the interaction of SPM and fiber dispersion. Kerr effect also introduces the effects of intra-channel nonlinear phase modulation and inter-channel cross-phase modulation (XPM) in temporal domain, and the effect of four wave mixing (FWM) in spectral domain.

Fig. 3 shows $Q_{avg}$ versus $P_{avg}$, in which pre-chirping is optimized for each case. The optimal $P_{avg}$ is denoted as $P_{opt}$ and the maximum $Q_{avg}$ is denoted as $Q_{max}$. The use of higher average power requires larger $f_{pm}$. In the 1550-nm band with PTM, $Q_{max}$ (CRZ)> $Q_{max}$ (CNRZ)> $Q_{max}$ (RZ)> $Q_{max}$ (AC-NRZ). In this wavelength band, NAC signals are better than AC signals because their frequency chirpings are symmetric about their pulse shapes and their pulse qualities are better during transmission. The pulse qualities of the four signal formats follow the same order as $Q_{max}$. In the 1585-nm band with DTM, $Q_{max}$ (AC-RZ)> $Q_{max}$ (AC-NRZ) > $Q_{max}$ (CRZ)> $Q_{max}$ (CNRZ). In the

1535-nm band also with DTM, the preferred order of the four formats is about the same as in 1585-nm band except that $Q_{max}$ (CRZ) is slightly larger than $Q_{max}$ (AC-NRZ). In the two wavelength bands, $Q_{max}$ (AC-NRZ) and $Q_{max}$ (CRZ) are about the same but the $P_{opt}$ of AC-NRZ signal is higher. The spectral power distributions of the four signal formats are all broadened resulting in less spectral nonlinear effects but the distribution of CRZ signal is more uniform. Without pre-chirping, Q factor of RZ signal is better than NRZ signal because there is less dispersive wave after optimal PDC for RZ signal owing to better restoration of pulse shape. Therefore the $Q$ factor of RZ signal is essentially better than NRZ signal for the long distance transmission. AC signals have the advantage of reduced nonlinear interaction between intra-channel neighboring bits so that higher signal power can be used. Therefore, the $Q$ factor of AC signal is better than NAC signal for DTM in this respect. Among the four signal formats, the performance with AC-RZ signal is best. Note that $P_{opt}$ of AC-RZ is larger than CRZ signal so that its signal-to-noise ratio (SNR) is improved

Raman effect causes the power of high frequency channel transfer to low frequency channel, which is known as Raman crosstalk. The dash lines in Fig. 3 show $Q_{avg}$ versus $P_{avg}$ with Raman effect. As only eight channels are considered for each wavelength band, Raman crosstalk is not significant and only results in slight degradation of $Q_{avg}$. It is noticed that the degradation is larger for 1550-nm band with PTM. As signal peak power is high in temporal domain, Raman crosstalk is more serious than the other two wavelength bands with DTM. It seems that DTM is perferred for designing the dispersion map of the wideband WDM system in which Raman effect is important. However the maximum $Q$ factor of CRZ signal in 1550-nm band is high as is shown in Fig. 3. Further studies are required to compare the performances of the WDM systems with the CRZ signal operated with PTM and with the AC-RZ signal operated with DTM when Raman crosstalk is important.

## 四、計畫成果自評

The dispersion-managed long-haul WDM optical communication systems with CRZ, AC-RZ, CNRZ, and AC-NRZ signals are studied. The optimal signal power for the maximum $Q$ factor of each signal format is shown. For the case of well dispersion compensation, signal transmission is operated with PTM and CRZ is the best signal carrier. For the other two cases of highly over and under dispersion compensation, signal transmission is operated with DTM and AC-RZ is the best signal carrier. The result of this project has been submitted to Journal of Lightwave Technology.

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## 六、圖表

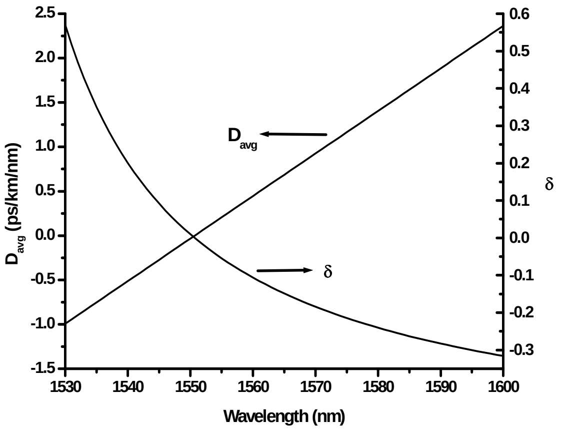


Fig.1 Path-averaged dispersion $D_{avg}$ and over dispersion compensation ratio δ versus wavelength.

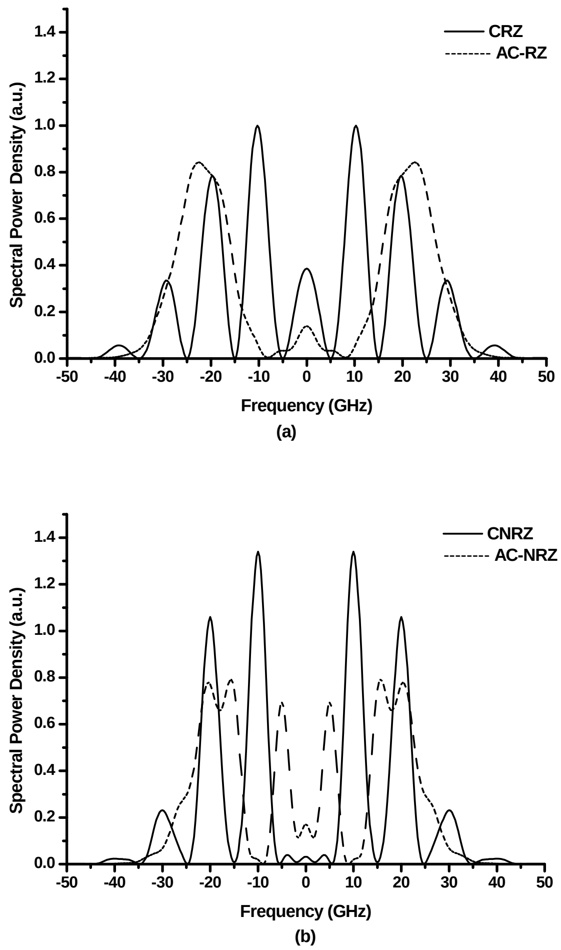


Fig. 2 Spectra of two neighboring signal pulses for the (a) CRZ, AC-RZ, and (b) CNRZ, and AC-NRZ with $f_{pm}$= 25 GHz and $P_{avg}$ = 1.0 mW.

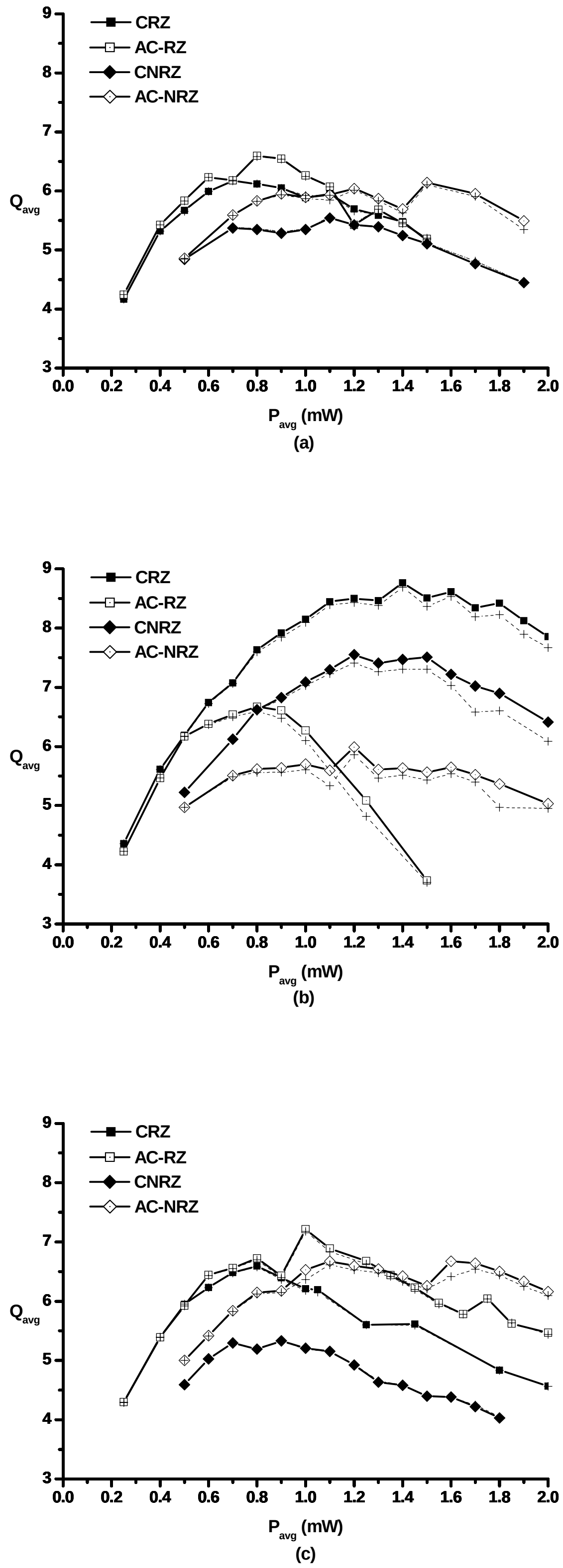


Fig.3 $Q_{avg}$ versus $P_{avg}$, for (a) 1535-nm band, (b) 1550-nm band, and (c) 1585-nm band. The thick lines show the cases without Raman effect. The thin dash line with "+" symbol near each thick line is the corresponding case with Raman effect.