行政院國家科學委員會補助專題研究計畫 **■成果報告**
□期中進度報告

波分多工被動光纖網路和光纖微波系統中的瑞利背向散射噪音模型, 分析, 及緩和研究

Rayleigh Backscattering Noise Modeling, Analysis and Mitigation for DWDM Passive Optical Networks and Radio-over-Fiber Networks

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執行期間：　97 年 8 月 1 日至 100 年 7 月 31 日

執行機構及系所：交通大學 光電工程系（所）

計畫主持人：鄒志偉副教授

成果報告類型(依經費核定清單規定繳交)：□精簡報告　■完整報告

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中　華　民　國　100 年　10　月　23　日

行政院國家科學委員會專題研究計畫成果報告

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Rayleigh Backscattering Noise Modeling, Analysis and Mitigation for DWDM Passive Optical Networks and Radio-over-Fiber Networks (3/3)

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一、中文摘要

現在的有線網路基於光纖到戶(FTTH)技術可以給用戶提供巨大的帶寬服務，但是對於漫遊連接就不夠靈活。因此，結合有線和無線服務在單一未來高帶寬接入網路可以使成本減低，同時滿足固定用戶和移動用戶的需求。這種混合接入網路可以由光纖微波(ROF)和波分復用被動光網路(WDM-PON)來實現。

本計劃主要探討波分多工被動光纖網路和光纖微波系統中的瑞利背向散射噪音模型,分析,及緩和研究。在第一年(97-98)我們已說明瑞利背向散射(Rayleigh backscattering)干擾噪音是載波分佈混合光接入網路的重要限制因素之一。由於之前的瑞利背向噪音模型具有不同的限制，我們成功地研究一個易實現，可有效操作的新型模型。我們已經進行了瑞利反向散射所產生的干涉噪音作理論分析。要有效地緩和瑞利背向散射，我們可以以新穎的光調變技術把上行訊號和載波的頻譜分間，如在第二年(98-99)我們提出新型的單邊帶過制載波 (SSB-CS) 訊號，實驗顯示SSB-CS具有極高的瑞利背向散射噪音容差值。另一種有效緩和瑞利背向散射的技術是把上行訊號和載波分別在不同的光路中傳輸，如在第三年(99-100)我們提出新型的環型被動光網路，利用光循環器與光柵使上行訊號和載波分開。最後更利用波長分裂(wavelength splitting, WS) 的方法，成功實驗具有極高瑞利背向散射噪音容差值的波分多工被動光纖網路和光纖微波的系統。

關鍵詞：瑞利背向散射噪音緩和，被動光網路，光纖微波

Abstract

Today's wired networks based on fiber to the home (FTTH) access technologies provide huge bandwidth to users but are not flexible enough to allow roaming connections. Therefore, the integration of wired and wireless services for future access networks will lead to convergence of ultimate high bandwidth for both fixed and mobile users in a single, low cost platform. This can be accomplished by using radio-over-fiber (ROF) systems and wavelength division multiplexed passive optical network (WDM-PON) to provide wireless and wired applications.

This NSC project focus on the research of Rayleigh backscattering (RB) noise modeling, analysis and mitigation for WDM passive optical networks (PONs) and radio-over-fiber (ROF) Networks. In the first year (2008-2009), RB interferometric beat noise is considered as one of the most limiting factors for the cost effective carrier-distributed PON and ROF access networks. Due to the different limitations of previous Rayleigh noise modeling, a novel modeling approach that can be easily realized and used efficiently to study the performance of noise mitigation has been successfully developed. The various noise contributions are derived from the power spectral densities (PSDs) of the optical signals and the performance of the scheme is then modeled analytically. For effective RB beat noise mitigation, we can use novel modulation schemes to reduce the spectral overlap between the upstream signal and the distributed optical carrier. In the second year (2009-2010), we proposed and investigated the RB noise mitigation scheme by using single sideband carrier suppressed (SSB-CS) modulation scheme. Experimental results show that the RB tolerance can be improved due to the reduced spectral overlap between the uplink signal and the RB noises. Besides using novel modulation schemes, we can also reduce the RB noise by separating the fiber paths between the upstream signal and the distributed optical carrier. In the third year (2010-2011), we proposed and demonstrated a ring-based PON. By using optical circulators and fiber Bragg grating, we can separate the transmission paths between the upstream signal and the distributed optical carrier, hence high RB tolerance can be measured. Finally, we have demonstrated a high RB tolerance heterogeneous optical wired (PON) and wireless (ROF) networks using wavelength splitting (WS).

Keywords: Rayleigh backscattering mitigation, Passive optical network, Radio-over-fiber

二、緣由與目的

In a wavelength division multiplexed (WDM) network, one of the most critical issues is the cost of the laser source used in the cost-sensitive subscriber side where the wavelengths for subscribers should be precisely aligned with an associated WDM link. Recently, PON architecture with centralized light source (CLS) has been proposed to reduce the cost by removing the laser source from the subscriber side. This can be achieved by employing a wavelength insensitive reflective modulator at the customer optical networking unit (RONU) together with a seed light provided from the central office (CO) for wavelength addressing. However, a loop-back network will suffer from the interferometric noise caused by Rayleigh backscattering (RB), which interferes with the uplink signal at the receiver (Rx) at the CO. Due to different limitations of previous Rayleigh noise modeling; a novel modeling approach is highly required. Hence in the first year, a novel RB modeling approach derived from the power spectral densities of the optical signals are built.

For effective RB mitigation, we can use novel modulation schemes to reduce the spectral overlap between the upstream signal and the distributed optical carrier. Several methods have been proposed such as using phase modulation induced spectral broadening and offset optical filtering scheme; or using wavelength shifting in a cascade modulators. However, these methods mentioned above are not power-efficient for the power-budget-sensitive PON (more than half of the uplink power will be filtered out by the offset filtering schemes or high insertion loss in the cascade modulator scheme). In the second year, we propose and investigate the RB noise reduction by using a dual-parallel Mach-Zehnder modulator (DP-MZM). By employing single sideband-carrier suppressed (SSB-CS) modulation scheme, the RB tolerance can be improved due to the reduced spectral overlap between the upstream signal and the RB noises.

Besides using novel modulation schemes, we can also reduce the RB noise by separating the fiber paths between the upstream signal and the distributed optical carrier. In the third year, we propose and demonstrate a RR circumvention architecture for the ring-based PON. RB can be significantly avoided since the RB and the upstream signal are traveling in opposite directions. Finally, we propose and demonstrate a heterogeneous optical access network using wavelength-splitting (WS) at remote-node (RN) to mitigate the RB noises. A pair of continuous wave carriers is generated from each laser for wired (PON) and wireless (ROF) applications respectively. Results show that the scheme can effectively mitigate RB noises.

三、研究成果

This project focuses on the research of Rayleigh backscattering (RB) noise modeling, analysis and mitigation for WDM PONs and ROF networks. Due to different limitations of previous RB noise modeling, a novel modeling approach that can be easily realized and used efficiently to study the performance of noise mitigation has been successfully developed. The various noise contributions are derived from the power spectral densities (PSDs) of the optical signals. We characterized experimentally [1] and theoretically [2] different contributions of the RB in a carrier-distributed PON at different optical signal to Rayleigh noise ratios (OSRNRs). Recent achievement of OFDM PON has been presented in **CLEO'08 post-deadline paper** in USA [3]. The achievements of the project have generated invited paper, invited talks and book chapter. We are invited to present our research achievements and impact of the FTTH for Taiwan in the Special Issue of the **IEEE LEOS Newsletter** about FTTx [4]. We has also been invited to contribute 2 **Book Chapters** in "Optical Access Networks and Advanced Photonics: Technologies and Deployment Strategies," IGI Global Publishing [5] and in "Advances in Lasers and Electro Optics," In-Tech Publishing [6]. Our results and achievement in long-reach PON has been cited by Ref/Text Book: "Next-Generation FTTH Passive Optical Networks: Research towards unlimited bandwidth access," edited by Josep Prat, Springer, 2008. We are also invited to present our researches of FTTx in international conferences, such as:

- IEEE Photonics Society Annual Meeting 2010 (formerly LEOS Annual Meeting) in USA [7],
- Photonic West 2009 in USA [8],
- International High Speed Intelligent Communication 2010 (HSIC 2010) in Singapore [9],
- OECC 2011 in Taiwan [10]
- OECC 2009 in Hong Kong [11].

We have summarized the main achievements below:

(1) Rayleigh backscattering modeling using power spectral density [1, 2]

Carrier distributed WDM-PONs provide many attractive features, however, when a single drop fiber is used to reach the customer, the carrier distributed from the head-end office and the upstream signal must share the same path, giving rise to interferometric beat noise caused by RB. The maximum split ratio achievable in the PON is limited by the levels of RB and back reflection present in the system. RB is generated by the distributed reflections caused by the random index fluctuation along the silica optical fiber. The RB noise is partially polarized in nature, with a colored power spectral density (PSD) proportional to the PSD of the generating input signal. This is different from the ASE, which is typically assumed to be a white noise. In the project, we identified two main contributions to the RB noise. Fig. 1.1 shows the two dominant contributions to the RB in the carrier distributed PONs, which interfere with the upstream signal at the receiver (Rx). The first contribution, Carrier-RB, is generated by the backscatter of the continuous wave (CW) carrier being delivered to the reflective ONU (RONU). The second contribution, Signal-RB, is generated by the modulated upstream signal at the output of the RONU. Backscattered light from this upstream signal re-enters the RONU, where it is re-modulated and reflected towards the Rx. The RB noise is partially polarized in nature, with a colored PSD proportional to the PSD of the input signal. Hence, the spectra of Carrier-RB and the CW carrier are the same, while the Signal-RB is modulated twice by the RONU and has a broader spectrum. The relative impact of the two components depends on the exact network configuration and hence, for a full understanding, separate analysis of each effect is needed.

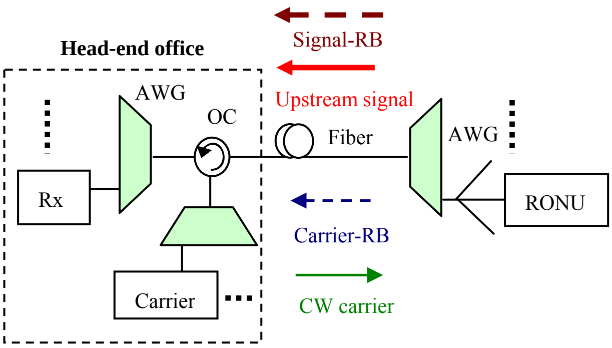

Fig. 1.1. Schematic of WDM PON using centralized light source. AWG: arrayed waveguide grating, OC: optical circulator, Rx: receiver, Carrier-RB and Signal-RB: carrier and signal generated Rayleigh backscattering.

A theoretical derivation of the RB properties and of the interferometric noise that it generates have been successfully achieved [2]. The actual spectrum of the high speed modulated signal needs to be considered in order to obtain an accurate prediction of the system performance. The noise generated by the beating of signal and RB:

$$\sigma_{s,b}^2 = \Re^2 \int_{-\infty}^{+\infty} |H_e(f)|^2 k[S_s(f)*S_b(f)+S_b(f)*S_s(f)]df,$$

where $S_s(f)$ and $S_b(f)$ are the PSD of upstream and backscattering signal respectively. They may be reshaped by the optical filter inside the Rx and the AWGs. * denotes deterministic cross-correlation, $\Re$ is the photodetector responsivity, $He(f)$ is the photodetector normalized frequency response, such that $He(0) = 1$. The noise generated by the RB beating with itself

$$\sigma_{b,b}^2 = \Re^2 \int_{-\infty}^{+\infty} |H_e(f)|^2 \frac{1+p^2}{2} S_b(f)*S_b(f)df,$$

where k and p are the polarization coefficients, with $p=2k-1$. The polarization coefficient k equals to 1 for completely polarized backscattering ($p=1$) aligned with the signal polarization and k =0.5 for a completely depolarized backscattered field ($p=0$). In practice, roughly 1/3 of the RB light is polarized, giving k≈0.667 and k≈0.333, respectively for signal co- and cross-polarized with respect to backscattering. Results from the model are in good agreement with the experiments [12, 13], showing that we can use the RB model to predict the network performance. Besides, the RB performances of the orthogonal frequency division multiplexed (OFDM) signals are characterized for the first time [14-16]

(2) RB noise reduction by using SSB-CS modulation [17 – 20]

We propose and demonstrate a long-reach (LR) PON with the capability of RB noise mitigation. By using the upstream signal wavelength-transition generated by a dual-parallel Mach-Zehnder modulator (DP-MZM) based colorless reflective optical networking unit (RONU), the spectral overlap among the upstream signal and the RB noises can be minimized. Hence, due to the achievement of effective RB mitigation, a 100 km LR-PON with a high split-ratio of 512 is demonstrated using 10 Gb/s non-return-to-zero (NRZ) downstream and 2.5 Gb/s NRZ upstream signals.

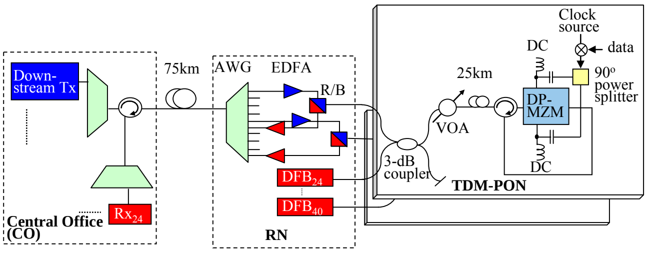

Fig.2.1. Architecture of the DWDM LR-PON using DP-MZM. R/B: red/blue filter, RN: remote node, VOA: variable optical attenuator.

Fig. 2.1 shows the proposed architecture of the DWDM LR-PON. For the upstream signal, in the RN a CW carrier at 1548 nm was launched to a 3-dB fiber coupler, a variable optical attenuator (VOA), which was used to emulate the PON split-ratio, and a 25 km drop single-mode fiber (SMF), before entering the ONU. In the colorless ONU, a loop-back configuration was achieved by an optical circulator (OC). The distributed CW carrier was coupled into the DP-MZM. It was electrically driven by a 10 GHz RF up-converted 2.5 Gb/s NRZ signal at pseudo-random binary sequence (PRBS) 2^{31}-1 in-phase and quadrature-phase respectively. The upstream single sideband carrier suppressed (SSB-CS) signal was then sent back to the CO through the same drop fiber, a red/blue (R/B) filter and an arrayed waveguide grating (AWG) (Gaussian shaped, 3-dB width of 50 GHz) at the RN. Then the upstream signal was sent back to the receiver (Rx) at CO via 75 km SMF feeder fiber. No dispersion compensation was used in the experiment.

Fig. 2.2 shows the measured optical spectra (resolution of 0.01 nm) of the distributed CW carrier and the SSB-CS NRZ upstream signal after the RONU. The suppression ratio of the upstream signal and the center wavelength are > 18 dB. The RB tolerance can be significantly improved by the reduction in the spectral overlap.

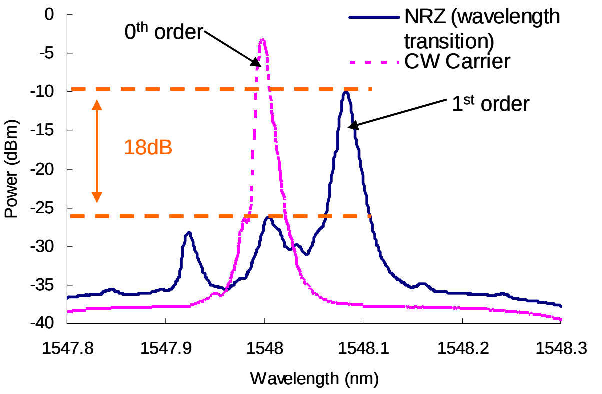

Fig. 2.2. Measured optical spectra. Solid line: SSB-CS uplink signal. Dotted line: centralized light source (CLS).

Fig. 2.3(a) and (b) show the bit-error rate (BER) performance of the upstream SSB-CS NRZ signal and the conventional NRZ in the LR-PON respectively. We measured ~5 dB power penalty in the SSB-CS signal when the split-ratio was 512 (VOA set at >-26 together with the 3-dB fiber coupler prior the VOA), without an error-floor. In Fig. 2.3(b), the conventional NRZ was not able to achieve 64-split and an error-floor appeared at BER of 10^{-7}. BER cannot be measured at split-ratio of 512 at the conventional NRZ case due to the nearly complete eye-closure (inset of Fig. 2.3(b)).

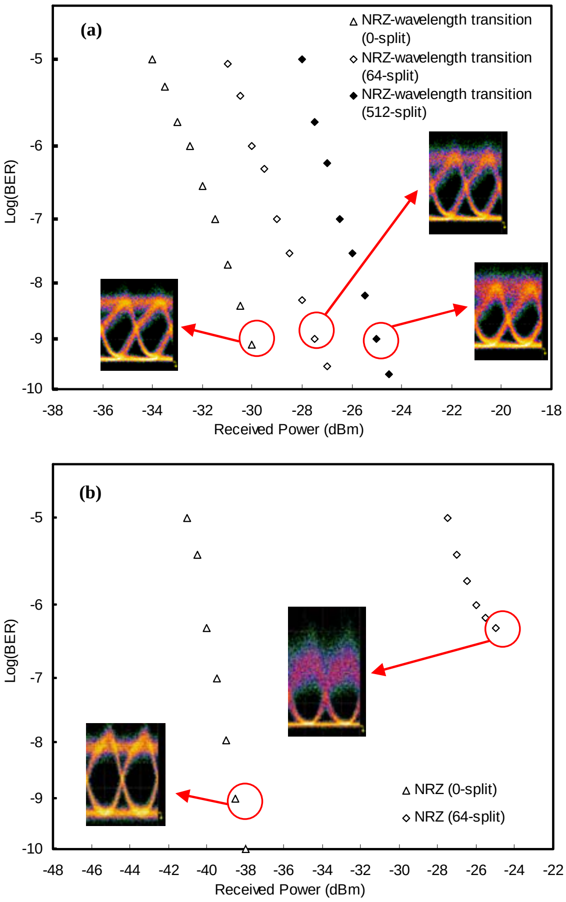

Fig. 2.3. BER performances of the 2.5 Gb/s upstream signals (a) using SSB-CS and (b) conventional NRZ signal. Insets: corresponding eye diagrams Insets show the corresponding eye diagrams.

In conclusion, by using the SSB-CS upstream signal generated by a commercially available DP-MZM based colorless ONU, both kinds of RB noise sources can be effectively mitigated. A reach extension from typical 20 km PON to 100 km LR-PON with split-ratio increases from 64 to 512 is achieved in the proposed network architecture.

(3) Rayleigh backscattering circumvention in ring-based PON [21]

Fig. 3.1 shows the proposed ring-based WDM PON. The CW optical carrier sent from the CO is traveling in the counter-clockwise (CCW) direction. At the RN, wavelengths will be dropped according to the wavelength selection by the tunable fiber Bragg gratings (FBGs). The dropped CW and the downstream signal will be distributed to different ONUs in the tree-based network. A red-blue filter (RBF) at each ONU separated the CW and downstream signals. The CW will be modulated to produce the upstream signal. It will be send back to the CO also in the CCW direction.

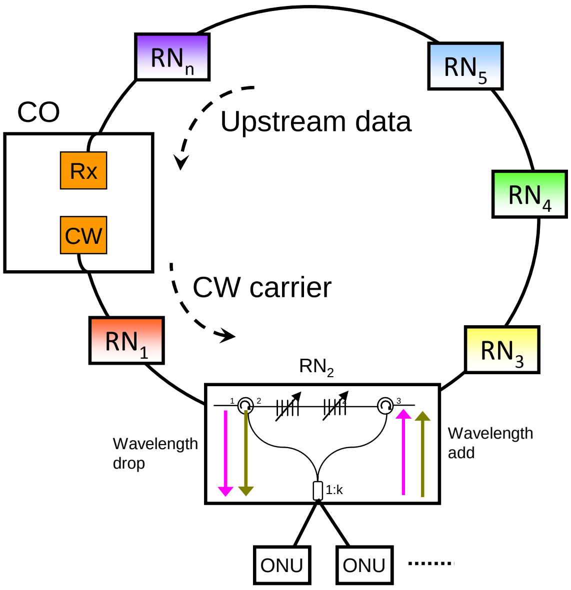

Fig. 3.1. Architecture of the proposed network. RN: remote node, CO: central office, ONU: optical networking unit.

BER measurements were performed at 2.5 Gb/s and 1.25 Gb/s for the upstream signal and 10 Gb/s for the downstream signal, as shown in Fig. 3.2. We also tested the split-ratio of the TDM access network by using different types of splitters. Changing the split-ratios from B2B to 64 also changes the input powers to the RSOA. This changes the signal to amplified spontaneous emission (ASE) ratio, and hence causes power penalty as shown in Fig. 3.2. When the split-ratio is increased to 64, much higher power penalties are observed. Hence, the proposed ring-based hybrid WDM-TDM access network can be operated at about 64 split-ratios. Clear eye-opening can be achieved in both upstream and downstream signals at split-ratio of 64. As the upstream signal and the CW carrier generated RB are traveling in two different directions, RB can be effectively avoided.

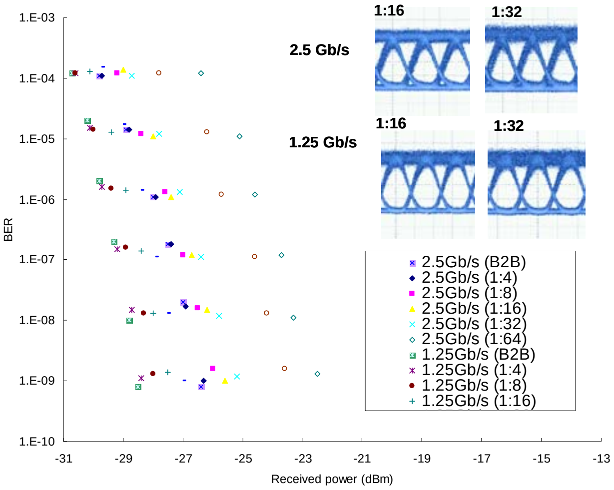

Fig. 3.2. Downstream and upstream BER measurements for the proposed networks at different bit rates and TDM split-ratios.

Finally, we propose and demonstrate a heterogeneous optical access network [22 – 24] using wavelength-splitting at remote-node to mitigate the RB noises [22]. As we have discussed before, for a typical carrier-distributed network, there are two types of RB noises, called carrier generated RB (Carrier-RB) and signal generated RB (Signal-RB), as shown in Fig. 3.3. We can observe from Fig. 3.3(e) that the upstream data signal, Carrier-RB and Signal-RB have a strong spectral overlap among them, producing high interferometric beat noises.

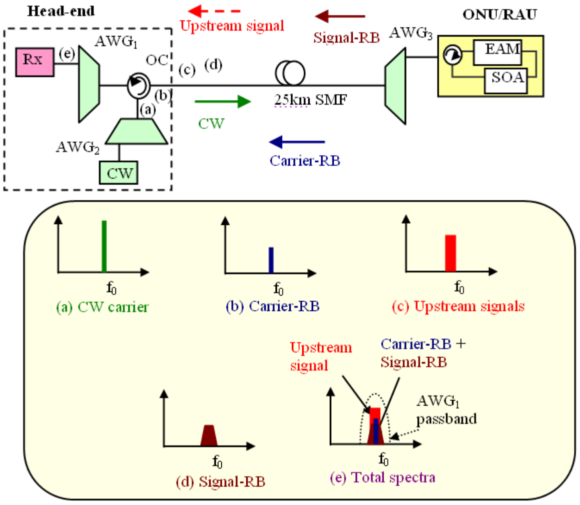

Fig. 3.3. Typical architecture of carrier distributed network with different schematic optical spectra at different locations.

Fig. 3.4 shows the proposed heterogeneous PON and ROF network with RB mitigation using WS. The CW carrier at optical frequency f_0 (Fig. 3.4(a)) distributed from the head-end will be modulated by a

Mach-Zehnder modulator (MZM) at the RN, which was electrically driven at Δf (25 GHz). The Carrier-RB will be generated by the CW carrier (Fig. 3.4(b)). The MZM at the RN will produce two optical sidebands which is 50 GHz apart with suppression of the center wavelength (Fig. 3.4(c)). Then, each sideband was filtered by a 50-GHz channel spacing arrayed waveguide grating (AWG_3), producing a pair of optical carriers ($f_0+\Delta f$, $f_0-\Delta f$) (Fig. 3.4(d), (e)). AWG_1 and AWG_3 were aligned to $f_0+\Delta f$, while AWG_2 was aligned to f_0. The two optical carriers ($f_0+\Delta f$, $f_0-\Delta f$) will be modulated at the ONU/RAU, forming the upstream signals for PON and ROF respectively (Fig. 3.4(f)).

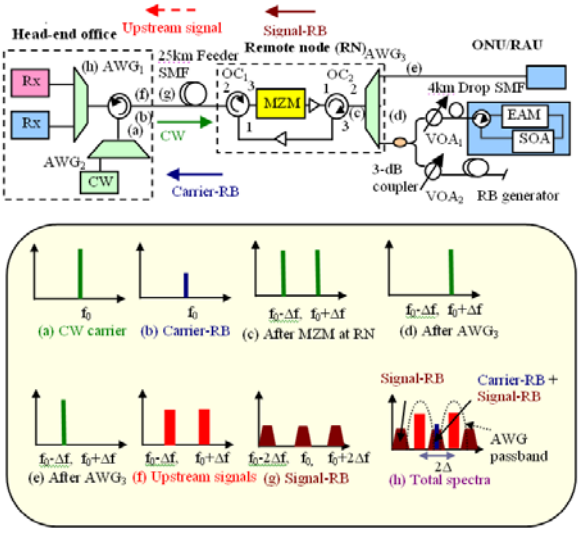

Fig. 3.4. Architecture of wired and wireless network using wavelength splitting, with different schematic optical spectra at different locations.

The upstream signals will bypass the MZM in the RN by using the two optical circulators (OCs) configuration, and detected by the head-end Rx. The upstream data will also be backscattered by the SMF towards the RN, where it will be wavelength split again, and blocked by the AWG_3. Back-reflection by the AWG_3 and the power leakage by the OC_2 will contribute to the Signal-RB launching to the head-end Rx (Fig. 3.4(g)). As shown in the schematic optical spectra of Fig. 3.4(h) at the head-end before AWG_1, the Carrier-RB is at frequency f_0, while the double-modulated Signal-RB has the frequency components of f_0 and $f_0\pm2\Delta f$. This shows that ideally there is no spectral overlap between the upstream data and both types of RB. Besides, the frequency components of the RB will be highly attenuated by the AWG_1 to further enhance the RB tolerance.

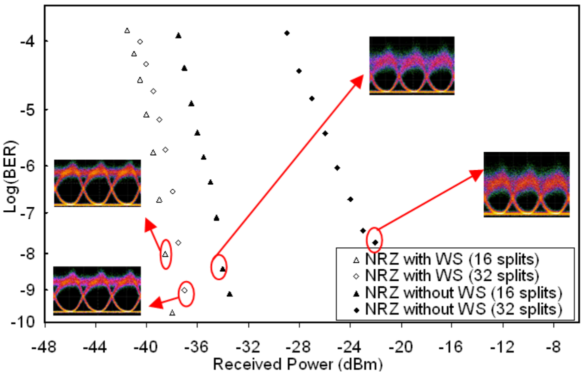

Fig. 3.5. BER of NRZ signals in the carrier distributed network with and without WS. Insets: corresponding eye-diagrams. Inset: Optical spectra of the f_0-Δf, f_0+Δf generated by the MZM.

We also evaluated the transmissions of the upstream signals by encoding the NRZ (for PON) and OFDM-QAM (for wireless) in the proposed network without and with using WS. 2.5 Gb/s pseudorandom binary sequence (PRBS) 2^{31}-1 NRZ data and 16-QAM OFDM signal were applied to the EAM respectively. The OFDM signal consisted of 16 subcarrier symbols and in 16-QAM format, generated by an arbitrary waveform generator with 4 GHz sampling rate. The OFDM signal was RF up-converted, occupying ~1 GHz of RF spectrum (from 62.5 MHz to 1,125 MHz).

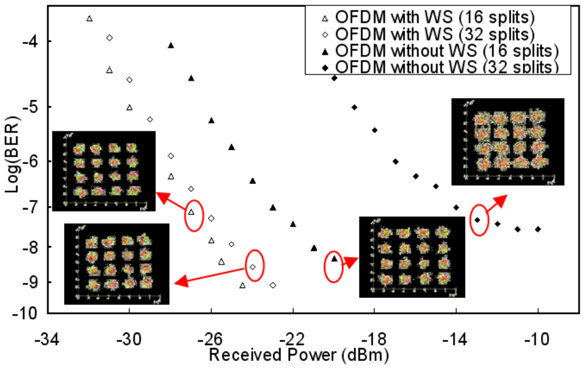

Fig. 3.6. BER of OFDM signals in the carrier distributed network with and without WS. Insets: corresponding constellation diagrams.

Fig. 3.5 and Fig. 3.6 show the BER performances of the NRZ and OFDM signals with and without WS. ~4 dB power penalty was observed in the NRZ signal (16 split-ratio) without WS. Error-floor at 10^{-8} was observed when the split-ratio was increased to 32. In Fig. 3.6, error-floors of

10^{-9} and 10^{-8} were observed in the OFDM signal with 16 and 32-split respectively when WS was not used. Results show that the proposed scheme can significantly mitigate the RB noises.

四、結論

The above researches have fruitful achievements and results have been published in several international journals and conference papers, invited papers, invited talks and 2 book chapters as described above. The achievements are brief summarized as: (1) A novel RB modeling derived from the PSDs of the optical signals was successfully established. We also identified two main contributions to the RB noise: Carrier-RB and Signal-RB. There is a good match between the experimental and modeling results in the Carrier-RB and Signal-RB analysis, showing the model is accurate. (2) By using the SSB-CS modulation generated by a commercially available DP-MZM based colorless RONU, both kinds of RB noise sources can be effectively mitigated. A reach extension from typical 20 km PON to 100 km LR-PON with split-ratio increases from 64 to 512 is achieved in the proposed network architecture. (3) Besides using advanced modulation to reduce the spectral overlap between the upstream signal and the distributed optical carrier, we proposed and demonstrated a RB circumvention architecture for the ring-based WDM PON. RB can be significantly avoided in the proposed architecture since the RB and the upstream signal were traveling in opposite directions. Experimental results showed that the proposed network can be operated at > 64 split-ratio. Finally, we demonstrated a heterogeneous optical wired (PON) and wireless (ROF) access network using WS at RN to mitigate the RB noises. A pair of CW carriers is generated from each laser source for wired and wireless applications respectively. Transmission experiments using NRZ and OFDM signals showed that the proposed network can effectively mitigate RB noises. We believe that the proposed architectures and sub-systems in this project could provide fertile foundation for the creation of wider market opportunities and new classes of applications. The invited papers and talks could also promote the image of Taiwan in the areas of communications and information technologies.

五、發表文獻

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[2] G. Talli, **C. W. Chow**, P. D. Townsend, “Modeling of modulation formats for interferometric noise mitigation,” *Journal of Lightwave Technology*, vol. 26, pp. 3190-3198, 2008 (SCI)

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可供推廣之研發成果資料表

■ 可申請專利　□ 可技術移轉　日期：100 年 10 月 23 日

國科會補助計畫	計畫：波分多工被動光纖網路和光纖微波系統中的瑞利背向散射噪音模型, 分析, 及緩和研究 計畫主持人：鄒志偉　計畫編號：NSC 97-2221-E-009-038-MY3 學門領域：光電
技術/創作名稱	Signal Remodulated Wired/Wireless Access using Reflective Semiconductor Optical Amplifier with Wireless Signal Broadcast
發明人/創作人	C. W. Chow and C. H. Yeh
技術說明	In this investigation, we propose and demonstrate a signal remodulated wired/wireless network using reflective semiconductor optical amplifier (RSOA) as a colorless modulator in the optical networking unit (ONU) / remote antenna unit (RAU). Dark-return-to-zero (DRZ) and binary-phase-shift-keying (BPSK) signals are used for the downstream wired and wireless broadcast respectively. The downstream signal will be remodulated to produce the upstream non-return-to-zero (NRZ) signal.
可利用之產業 及 可開發之產品	產業：光纖通訊 產品：混合接取網路與光纖系統
技術特點	我們提出使用一組調變器能產生暗歸零碼(DRZ)和二相移相键控(BPSK)分別用在有線和無線混合接取網路，再通過調變下行訊號以產生上行信號，可以實現波長重用，並且進一步減少接取網路的成本。
推廣及運用的價值	根據此發明加以商品化的產品將在成本上具有優勢。

※　1.每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※　**2.本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※　3.本表若不敷使用，請自行影印使用。