行政院國家科學委員會專題研究計畫成果報告

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

計畫編號：97-2221-E-009-038-MY3
執行期限：97 年 8 月 1 日至 98 年 7 月 31 日
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一、中文摘要

爲跟上帶寬增長的需要，現存的接取網路需要一個很大的升級。這些網路還應該提供雙向，易安裝並且低成本的服務給每一位顧客。當前的有綫網路基於光纖到戶(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。從另一方面來看，雖然無綫網路具有移動性，但是並不能滿足高清電視(HDTV)和互動多媒體應用的大量帶寬要求。因此，結合有綫和無綫服務在單一未來高帶寬接取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。這種混合接取網路可以由光纖微波(ROF)和波分復用被動光網路(WDM-PON)來實現無綫和有綫的應用。

本報告將分成三部分:（1）瑞利背向散射(Rayleigh backscattering)干擾噪音被認爲是載波分佈混合光接取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。不同的噪音先由光信號的功率譜密度(PSD)導出，我們再對其特性進行分析。（2）由於正交頻分複用(OFDM)技術可有效減少光纖中的色散以及有高頻譜效率，我們進行 OFDM 訊號的瑞利背向散射干擾噪音的實驗分析，成功獲得 OFDM 信號在載波瑞利噪音(Carrier-RB)及信號瑞利噪音(Signal-RB)之下的特性。(3) 通過再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。因為 OFDM 信號頗受信號瑞利噪音的影響，我們利用雙重生源光纖(dual-feeder fiber) 成功展示一個不受瑞利背向散射噪音影響的 OFDM 波長重用長距離接取網路。

關鍵詞：瑞利背向散射噪音緩和，被動光網路，光纖微波

Abstract

A strong upgrade of existing access network is required in order to cope with the exponential increase of bandwidth demand. These networks should and also provide bi-directionality, feasibility, ease of installation, and lower cost per customer. 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. On the other hand, wireless networks offer mobility to users, but do not possess abundant bandwidth to meet the ultimate demand for high definition television (HDTV) distribution and interactive multimedia applications. Therefore, 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 report is divided into 3 sections: (1) Rayleigh backscattering (RB) interferometric beat noise is considered as one of the most limiting factors for the cost effective carrier-distributed FTTH and ROF access networks. Due to 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. (2) Since orthogonal frequency division multiplexed (OFDM) signal has the advantages of effectively mitigation of fiber chromatic dispersion and high spectral efficiency, we experimental analyze the RB performance of OFDM signal. We have characterized the Carrier-RB and Signal-RB performances of the OFDM signal. (3) Remodulation of downstream signal to generate upstream signal in the colorless ONU further reduces the cost by wavelength reuse. Since OFDM signal can be affected by the Signal-RB, we use dual-feeder fiber architecture to successfully demonstrate a signal remodulation OFDM long reach (LR)-PON.

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

二、緣由與目的

Rayleigh backscattering (RB) interferometric beat noise is considered as one of the most limiting factors for the cost effective carrier-distributed access networks. Due to different limitations of previous Rayleigh noise modeling, a novel modeling approach is highly required. Recently, OFDM signal has been extensively studied, and is considered as a promising candidate for future access network due to the high fiber chromatic dispersion tolerance and high spectral-efficiency. However, the research and the characterization of the OFDM signal when subjected to the RB interferometric beat noise in carrier distributed access network is missing. We quantify, for the first time, the performance of the OFDM signal when subjected to the noise generated by the two different components of RB that are present in the carrier distributed access network. We also studied the possibility of using OFDM for signal remodulation in the LR-PON. We demonstrated, for the first time, a carrier distributed OFDM LR-PON using dual-feeder fiber architecture to mitigate RB noise. Three different colorless optical networking unit (ONU) architectures are tested and compared. The overall research project will also identify the requirements of access networks for Taiwan in order to provide cost-effective PON deployment.

三、研究成果

Recent achievement of LR-PON using OFDM signal to mitigate fiber chromatic dispersion and achieve high split-ratio has been accepted in **CLEO'08 post-deadline paper** in USA [1]. There are a total of 24 post-deadline papers in this CLEO conference, and we are the only Taiwan research team among them. 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 [2]. We has also been invited to contribute a **Book Chapter** in "Optical Access Networks and Advanced Photonics: Technologies and Deployment Strategies," edited by I. P. Chochliouros and G. A. Heliotis, IGI Global Publishing [3]. It presents a comprehensive overview of emerging optical access network solutions to efficiently meet the anticipated growth in bandwidth demand. We are also invited to present the FTTx of Taiwan in international conferences, such as **Photonic West 2009 (USA)** [4] and **OECC 2009 (Hong Kong)** [5].

We have summarized our main achievements in the first year of the project by the following points:

(1) Rayleigh backscattering modeling using power spectral density.
(2) Rayleigh backscattering analysis of OFDM signal.
(3) OFDM signal remodulation LR-PON using dual-feeder fiber architecture to mitigate Rayleigh backscattering.

We then present our detailed description according to the above three main achievements:

(1) Rayleigh backscattering modeling using power spectral density

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 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.

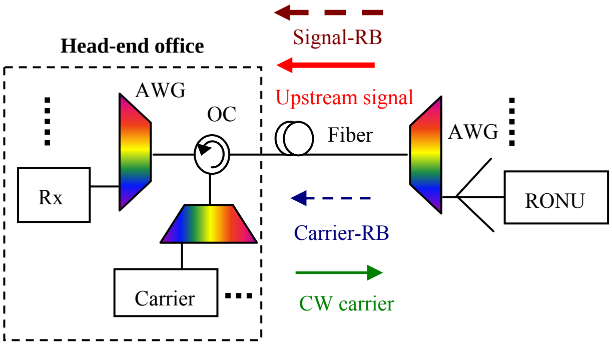

Fig. 1. Schematic of WDM PON using centralized light source. AWG: arrayed waveguide grating, OC: optical circulator, Rx: receiver, Carrier-RB and Signal-RB: carrier and signal generated Rayleigh backscattering.

A theoretical derivation of the RB properties and of the interferometric noise that it generates have been successfully achieved [6]. 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 [7, 8], showing that we can use the RB model to predict the network performance.

(2) Rayleigh backscattering analysis of OFDM signal

Recently, PON using OFDM is a subject of many research works [9]. Due to the high spectral efficiency of the M-quadrature amplitude modulation (QAM) used in the OFDM signal; low bandwidth optical components can be used. Additionally, the inherent advantage of OFDM frequency diversity transmission enables simple equalization of frequency response by baseband digital signal processing. The OFDM signal has a high tolerance to chromatic dispersion. This high tolerance is especially useful in PONs since distances between the head-end office and different ONUs cannot be fully dispersion compensated. Furthermore, it offers the prospect of integrating forward error correction (FEC) to improve transmission. However, previous works show that carrier-distributed OFDM-PON suffers form interferometric beat noise generated by RB. In this project, we quantify, for the first time, the performance of the OFDM-QAM signal when subjected to the noise generated by the two different components of RB that are present in the carrier-distributed OFDM PON.

We proposed two setups to analyze and quantify the Carrier-RB and Signal-RB tolerance of the OFDM-QAM upstream signal, as shown in Fig. 2 (a) and (b) respectively. They emulated the impairments of a real PON by generating two interfering signals in the upper and lower arms of the interferometer.

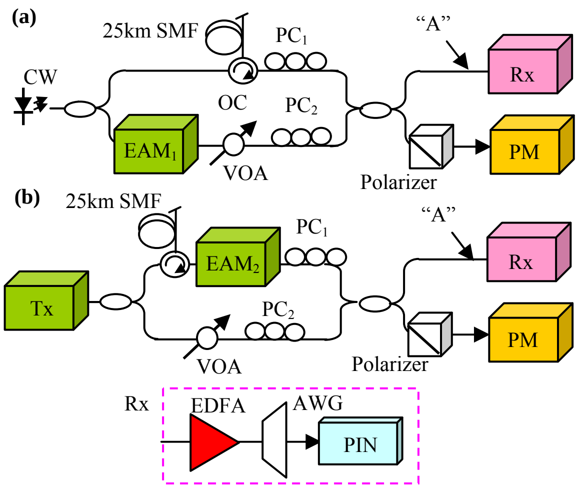

Fig. 2. Experimental setup to emulate (a) Carrier-RB and (b) Signal-RB. EAM: electro-absorption modulator, VOA: variable optical attenuator, PC: polarization controller, PM: power meter. Inset: Rx architecture, AWG: arrayed waveguide grating.

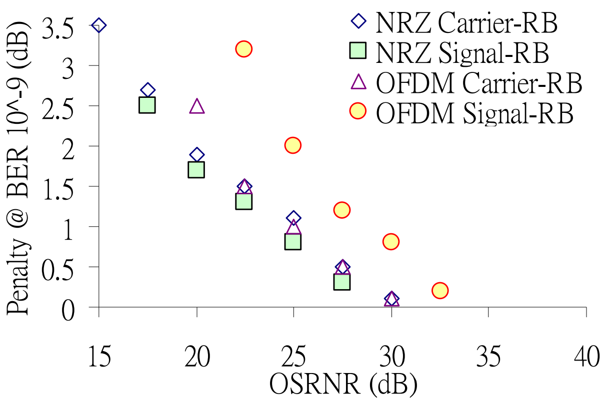

Fig. 3. RB noise performance at OFDM-QAM when compared with conventional NRZ formats.

The RB performance depends on the interferometric beat noise falling within the receiver bandwidth [10]. Fig. 3 shows the measured RB performances [11] by comparing the power penalties at bit-error-rate (BER) of 10^{-9}, as a function of optical signal to Rayleigh noise ratios (OSRNRs), which is defined as the ratio of total signal and total RB power at the input to the head-end (point "A"). The result shows that the Carrier-RB performance of OFDM-QAM is better than its Signal-RB performance. This is due to the fact that Carrier-RB beat noise is low frequency in nature, and the OFDM is frequency up-converted, as can be seem in Fig. 4. Hence, the beat noise mainly falls within the B_{gap}. The signal-RB has a wider spectrum than the OFDM signal due to the double modulation, and locates at the same frequency band as the OFDM signal; hence this generates much higher beat noise due to the complete spectral overlap. The RB performance of NRZ signal was also included. Results show that OFDM-QAM has similar Carrier-RB performance to NRZ, but poorer Signal-RB performance than NRZ. Fig. 4 shows the schematic RF spectra of the Carrier-RB and the Signal-RB of the OFDM-QAM signal, showing the low frequency nature of the Carrier-RB and the broad Signal-RB spectrum occupying the same frequency band as the upstream signal.

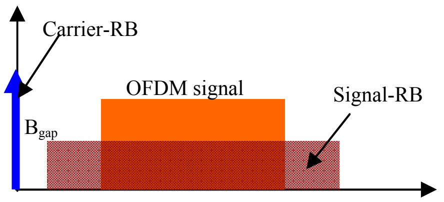

Fig. 4. Schematic RF spectra indicating the carrier-RB, signal-RB of OFDM signal.

(3) OFDM signal remodulation LR-PON using dual-feeder fiber architecture to mitigate Rayleigh backscattering

Signal remodulation has attracted a lot of researches for the past few years as one of the promising candidate for next generation PON [12-17]. Expensive transmitter (Tx) inside the ONU with distinct and specific wavelength has hindered the PON deployment. Network architectures with signal remodulation on the downstream channel for the upstream channel can reduce the cost of wavelength referencing, control and stabilization at the cost-sensitive ONU. A single wavelength is needed for both downstream and upstream signals, since wavelength is reused. Besides, the same colorless ONU can be used for all the customers.

In this project, we study, for the first time, the possibility of using OFDM for signal remodulation in the LR-PON. According to the analysis described in Section 2 of this mid-term report, RB noise can degrade the performance of a carrier-distributed PON using OFDM signal. Hence dual-feeder fiber architecture has been used to mitigate the RB noise in a carrier-distributed PON. Three different colorless ONU architectures: electro-absorption modulator (EAM)-based, reflective semiconductor optical amplifier (RSOA)-based and injection-locked Fabry-Perot laser diode (FP-LD)-based ONUs, are tested and compared.

If we consider a carrier-distributed PON with two stages of splitters such as the one in Fig. 5, where for clarity the arrayed waveguide grating (AWGs) are not shown, we can see clearly that most of the Carrier-RB power is generated by the optical carrier in the fiber before the first splitter, conventionally called feeder fiber. This is mainly due to the loss introduced by the first splitter and also because the feeder fiber usually accounts for most of the access length. The Carrier-RB generated before the first splitter cannot reach the Rx and thus it cannot interfere with the upstream signal. Although the Carrier-RB generated in the distribution and drop sections, and the Signal-RB still propagates to the Rx, the overall power is greatly reduced compared with a system with a single feeder fiber [18]. This scheme maintains the benefit of a single drop and distribution fiber in the path to each ONU, which could reduce the cost of fiber and fiber connections in the network. The circulator, normally used to inject the carrier in single-feeder schemes, is also not required, since the optical splitter employed to combine the two feeder fibers performs this function.

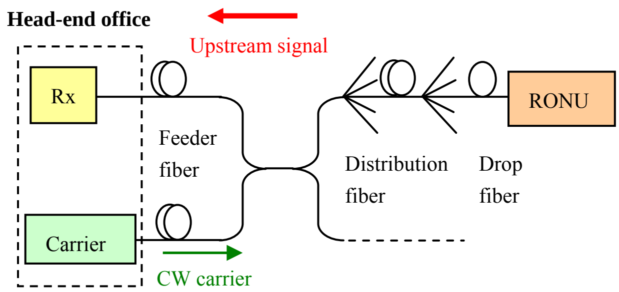

Fig. 5. Schematic of a carrier distributed PON using dual-feeder fiber architecture.

Fig. 6 shows the demonstration of a signal remodulation LR-PON. The downstream OFDM signal was applied to the EAM. The signal was then propagating through 90 km and 10 km of feeder and distribution/drop fibers respectively. At the ONU, 10% of downstream power was tapped out and detected by an optically pre-amplified Rx. The remain of the downstream signal was then launched into the colorless modulator at the ONU. We analyzed three different kinds of colorless modulators: EAM, RSOA and FP-LD. In each case, a 2.5 Gb/s non-return-to-zero (NRZ) data, pseudo random binary sequence (PRBS) pattern length of $2^{31}-1$, was used to directly modulate the colorless modulator.

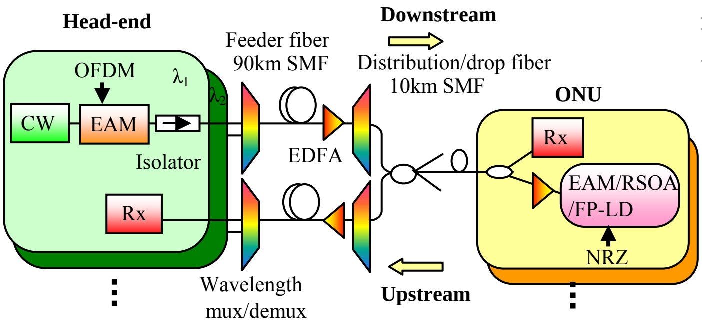

Fig. 6. Experimental setup of signal remodulation DWDM-PON. EAM: electro-absorption modulator, SMF: single mode fiber, EDFA: erbium-doped fiber amplifier, RSOA: reflective semiconductor optical amplifier, FP-LD: Fabry-Perot laser diode.

We studied the optimum extinction ratio (ER) of the downstream OFDM-QAM signal for both downstream and upstream links. As shown in Fig. 7, by decreasing the ER of the OFDM signal, higher residual background light can be provided for the upstream remodulation. When an EAM-based ONU is used, the intercepting point is at the position where the ER of OFDM is equal to ~3.7 dB, and it means 4 dB of power penalty will be introduced to both the upstream and downstream signals. We can see that RSOA-based and FP-LD-based ONUs performed better. By using the gain-saturation property of the RSOA or the injection locking property of the FP-LD, the downstream OFDM signal can be significantly suppressed, and these can increase the intercepting point to ~4.7 dB. This shows a power penalty improvement of 1 dB in the OFDM signal.

Since each modulator has its optimum condition, in the comparison, we selected the ER = 3.7 dB for the downstream OFDM signal. Fig. 8 shows the BER measurements of each signal at back-to-back (B2B) and after the 100 km LR transmission [19]. Insets show the constellation diagrams of OFDM signal at ER = 3.7 dB, output remodulated NRZ eye diagrams of FP-LD and RSOA when downstream OFDM at ER = 3.7 dB. We can observe clear open eyes after 100 km SMF transmission without dispersion compensation in each case. Error-free BER operation can be achieved for the proposed remodulation LR system.

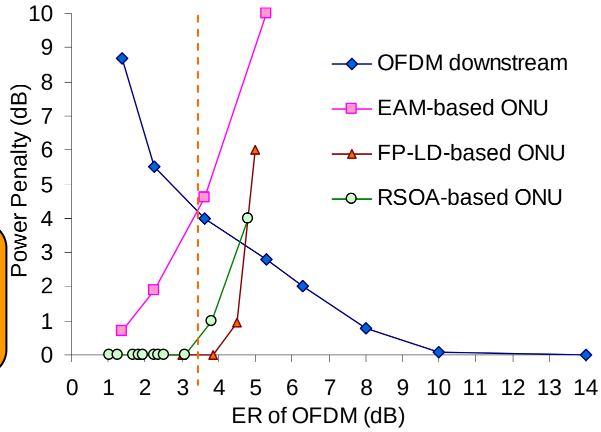

Fig. 7. Power penalties of downstream OFDM and upstream NRZ signals generated by different kinds of ONUs against different extinction ratio (ER) of the downstream OFDM signal.

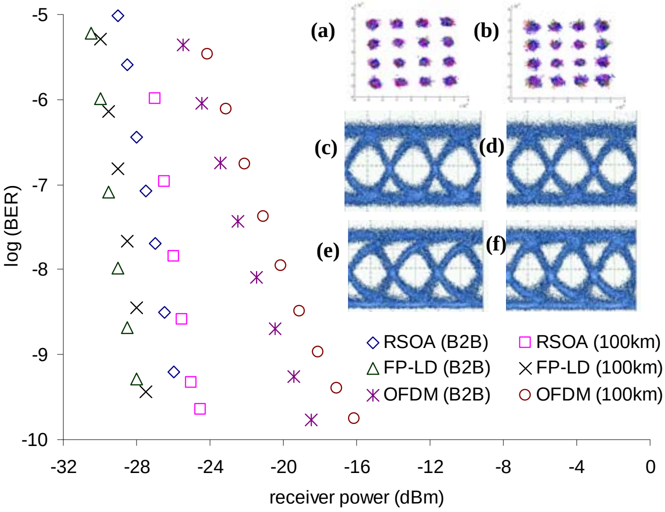

Fig. 8. BER measurements of different signals. Insets: constellation diagrams of OFDM signal at ER = 3.7 dB at (a) B2B, (b) 100km, output remodulated NRZ eye diagrams of FP-LD at (c) B2B, (d) 100km; and RSOA at (e) B2B, (f) 100km, when downstream OFDM at ER = 3.7 dB.

四、結論

The above researches have fruitful achievements and results have been published in several international journal and conference papers, invited papers and talks. The project mid-term report was divided into three sections: (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) Previous researches show that carrier-distributed OFDM-PON suffers form interferometric beat noise generated by RB. We quantified, for the first time, the performance of OFDM signal when subjected to the noise generated by the Carrier-RB and Signal-RB that are present in the carrier-distributed PON. The result shows that the Carrier-RB performance of OFDM-QAM is better than its Signal-RB performance. (3) We studied the possibility of using OFDM for signal remodulation in the LR-PON. We demonstrated a carrier distributed OFDM LR-PON using dual-feeder fiber architecture to mitigate RB noise. Three different colorless ONU architectures: EAM-based, RSOA-based and FP-LD-based, were tested and compared, showing that despite the polarization controlling issue, FP-LD can provide a greater downstream OFDM suppression and produce a better upstream data.

The above results will provide a solid foundation for the second and third year research project.

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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：98 年 5 月 30 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	室溫下利用 Fabry-Perot etalon 之多波長摻鉺光纖環型雷射
發明人/創作人	C. W. Chow, C. H. Yeh, C. H. Wang, F. Y. Shih, Y. F. Wu and S. Chi
技術說明	此研究中，我們在線性共振腔內利用一個 Fabry-Perot etalon 並且在室溫下使用一段長度可滿足多波長產生於 C-band 條件之最小公倍數的光纖共振腔，運用此方式提出並驗證一個簡單且具成本效益的摻鉺光纖(erbium-doped fiber, EDF)環型雷射。此外輸出波段的中心波長可分別調整在 1541.02、1551.32 和 1562.03 nm 上，而各別波段的波長間距為 0.34 nm。另外也有分析討論此多波長雷射的輸出穩定度。
	In this investigation, we propose and demonstrate a simple and cost-effective erbium-doped fiber (EDF) ring laser using a Fabry-Perot etalon inside a linear cavity and employing the accurate fiber cavity length to satisfy the least common multiple number for generating multiwavelength in C-band at room temperature. Furthermore, the centre wavelength of the lasing wavelength bands can be adjusted to 1541.02, 1551.32 and 1562.03 nm, respectively. The wavelength separation in each wavelength band is 0.34 nm. Moreover, the output stability of the multiwavelength laser has also been discussed and analyzed.
可利用之產業及可開發之產品	產業：光纖通訊與感測 產品：多波長光纖雷射與光纖感測系統
技術特點	我們提出使用線性共振腔的 Fabry-Perot etalon 與一段最佳光纖長度可以成為一個簡單的摻鉺光纖雷射系統，可以在室溫下產生 C-頻帶的多波長輸出。
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。**

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