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Research Article

Investigation and Suppression of Fiber Nonlinearities Using Injection-Locking in OFDM-WDM System

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The fiber nonlinearities play a major role in optical communication with respect to the system performance and transmission capacity. Here, fiber nonlinear impairments are investigated through consideration of several parameters of optical fiber system, such as fiber length and core effective area. We also demonstrate the mitigation of fiber nonlinearities by using single-stage injection-locking in 3×10 Gb/s OFDM-WDM system. This paper focuses on selection of appropriate bias current for slave laser to suppress the four wave mixing (FWM) crosstalk effects. These findings resemble the importance of single-stage injection-locking for FWM suppression for high-speed data communication.

1. Introduction

Over the time, the requirements for bandwidth have been increased critically. The different possible solutions have come up which include architectural modifications in terms of modulator design, advance modulation formats, and integration of wireless communication with optical fiber technologies. However, there are several issues that need to be resolved such as fiber dispersion, noise, and fiber nonlinearities. With increased power levels, the different fiber nonlinearities come into picture such as four wave mixing (FWM), self-phase modulation (SPM), cross-phase modulation (CPM), stimulated Raman scattering (SRS), and stimulated Brillouin scattering (SBS). Out of these effects, the FWM and SBS processes have significant potential to alter the performance of transmission systems, even if the systems are operated using narrow linewidth single frequency lasers [1, 2]. These effects become more critical to handle in higher-channel WDM system for long distance transmission. The FWM products result throughout the changes in refractive index of fiber core with respect to optical intensity. If the FWM products fall in transmission window of baseband signals, these can give rise to crosstalk between significant channels propagating through the fiber [3]. These effects are analogous to intermodulation distortion in case of electrical systems.

The efficiency of FWM products generally depends on the fiber-chromatic dispersion, transmission length, and the channel separation. Therefore, diverse research efforts have been reported to mitigate the crosstalk due to FWM in appropriate transmission system design [4–7]. Guo and Shu [8] reported the suppression of FWM crosstalk using Raman assisted fiber optical parametric amplifier (FOPA). The Raman assisted FOPA system offered unique power evolution of signals that helped obtain 7 dB decrease in FWM crosstalk. Zhu et al. [9] reported microwave signals generation based on a novel technique utilizing optical sideband injection and FWM. This technique can produce microwave signals with frequency octupling, 12- and 14-tupling. However, the several limitations can be seen in terms of bandwidth limited photodetector that allows the signal generation up to 18 GHz only. Recently, injection-locking has emerged as one of the most promising techniques for suppression of fiber nonlinearities. Jignesh et al. [10] proposed the injection-locking technique to compensate the interchannel nonlinear phase noise that occurs mainly due to XPM. The injection-locking strongly follows the XPM-phase distortion that can be partially cancelled with the help of homodyne receiver. No doubt injection-locking technique is very effective for microwave signal generation or XPM-phase noise cancellation; it can outperform other techniques in the suppression of other fiber nonlinearities also.

Here, the fiber length and core effective area are investigated in terms of their effects on FWM power. The suppression of FWM products using master-slave injection-locking is a new concept and not much explored. The selection of bias current for slave laser has a significant impact over the system performance in terms of suppression of FWM products.

2. Concept of Fiber Nonlinearities

The terms linear and nonlinear optics basically relate to intensity-independent and intensity-depenedent phenomenon, respectively. The linear impairments usually originate due to chromatic dispersion (CD), fiber loss, and polarization mode dispersion (PMD). On the other hand, the nonlinear impairments are caused by two different mechanisms: (i) inelastic scattering of photons inside the fiber (e.g., SBS and SRS nonlinearities) and (ii) changes in the refractive index of fiber core via changes in optical power intensity (e.g., FWM, SPM, and XPM nonlinearities) [11]. Out of these nonlinear effects, FWM is a third-order nonlinearity that comes into picture when two or more than two signals are propagated through the fiber. The number of FWM crosstalks increases rapidly with the number of propagated signals (N) as $(1/2)N^3(N-1)$ [12]. The power level of FWM products is strongly dependent on channel spacing, fiber dispersion, and core effective area. The magnitude of FWM can be expressed [13, 14] as

$$P_{FWM} = \frac{\eta}{9} D^2 \gamma^2 P_i P_j P_k e^{(-aL)} \left\{ \frac{\left[1 - e^{(-aL)}\right]^2}{a^2} \right\}, \quad (1)$$

where η denotes the FWM efficiency, D denotes the CD of the fiber, P_i, P_j, and P_k denote input optical power with frequency f_i, f_j, and f_k, respectively (given that $k \neq i$), L denotes the fiber length, α denotes the attenuation coefficient, and γ is the nonlinear coefficient of the fiber, given as

$$\gamma = \frac{2\pi \mathrm{n}_2}{\lambda \mathrm{A}_{\mathrm{eff}}}, \quad (2)$$

where n_2 is the nonlinear refractive index of optical fiber, λ is the operating wavelength of the fiber, and A_{eff} is the core effective area. The FWM efficiency can be expressed [15] as

$$\eta = \frac{\alpha^2}{\alpha^2 + \beta^2} \left[1 + \frac{4 \exp(-\alpha L) \sin^2(\Delta\beta L/2)}{\left(1 - \exp(-\alpha L))^2\right)} \right], \quad (3)$$

where $\Delta\beta$ is the phase-matching factor and can be expressed as

$$\begin{aligned} \Delta\beta &= \beta - \beta_o \\ &= 2\pi(f - f_o)\frac{d\beta}{d\omega} + \frac{1}{2}2\pi(f - f_o)^2\frac{d^2\beta}{d\omega^2} \\ &\quad + \frac{1}{6}2\pi(f - f_o)^3\frac{d^3\beta}{d\omega^3} + \frac{1}{24}2\pi(f - f_o)^4\frac{d^4\beta}{d\omega^4} \\ &\quad + \frac{1}{120}2\pi(f - f_o)^5\frac{d^5\beta}{d\omega^5}. \end{aligned} \quad (4)$$

Here, dispersion parameters are considered up to fifth order. The phase-matching factor varies along with the wave propagation through the fiber such as

$$\Delta\beta' = \Delta\beta - \gamma m (P_1 P_2 P_3) \left[\frac{1 - xp\left(-\alpha L_{eff}\right)}{\alpha L_{eff}} \right], \quad (5)$$

where m is an integer and L_{eff} is the effective fiber length, i.e., $L \gg L_{eff}$. Further, the effect of different parameters of optical fiber on FWM crosstalk is investigated in the next section.

3. Investigation of FWM Effects

In order to investigate the effect of FWM-induced crosstalk, the powers of all input channels are considered equal. The other parameters are considered as per the ITU:T recommendation G.653 as fiber CD (D) is 0.5 ps/km nm along with 0.25 dB/km attenuation factor (α). The dispersion effect is considered up to 5th order with $m = 0.63$. The effective core area is 67.43 μm^2 and fiber nonrefractive index (n_2) is chosen as 2.68×10^{-20} m^2/W. Figure 1 shows the FWM crosstalk induced in optical fiber system due to combined effect of dispersion up to fifth order. As the fiber length increases, the FWM power products become more critical to handle (refer to Figure 1(a)). Similarly, fiber effective area also puts limitation on its further decrement beyond 50 μm^2 that can give rise to higher FWM nonlinearities (refer to Figure 1(b)).

4. Suppression of FWM Effects using Injection-Locking

As already discussed in Section 3, the optical transmission power, channel length, and the core effective area put several limitations on the system in terms of their careful selection in order to suppress the fiber nonlinearities, i.e., FWM. The FWM effects occur due to confinement of optical field to the small effective area of fiber core over long distances. However, the core effective area as well as the optical transmission power and/or channel length cannot be increased and decreased respectively beyond certain limits. Therefore, we have put efforts over the suppression of FWM products by laser injection-locking technique. The injection-locking can suppress the FWM products by deviating the spacing between master and slave operating wavelengths [16]. The simulation setup for 3-channel OFDM-WDM system is shown in Figure 2. The generation of OFDM signals is presented elsewhere [17]. In brief, OFDM signal makes use of N closely spaced orthogonal subcarriers that are transmitted in parallel configuration. The advanced modulation technique (i.e., 16-quadrature amplitude modulation) is used to separately modulate the subcarriers. In the OFDM technique, guard band is also provided at the end of each OFDM stream in order to reduce the intersymbol interference (ISI). The three OFDM signals are generated and separately modulated with the help of Mach-Zehnder modulator (MZM) at different wavelengths. The MZM can generate optical combs with excellent properties in terms of spectral flatness. The MZM can also cause nonlinear effects depending on its static phase

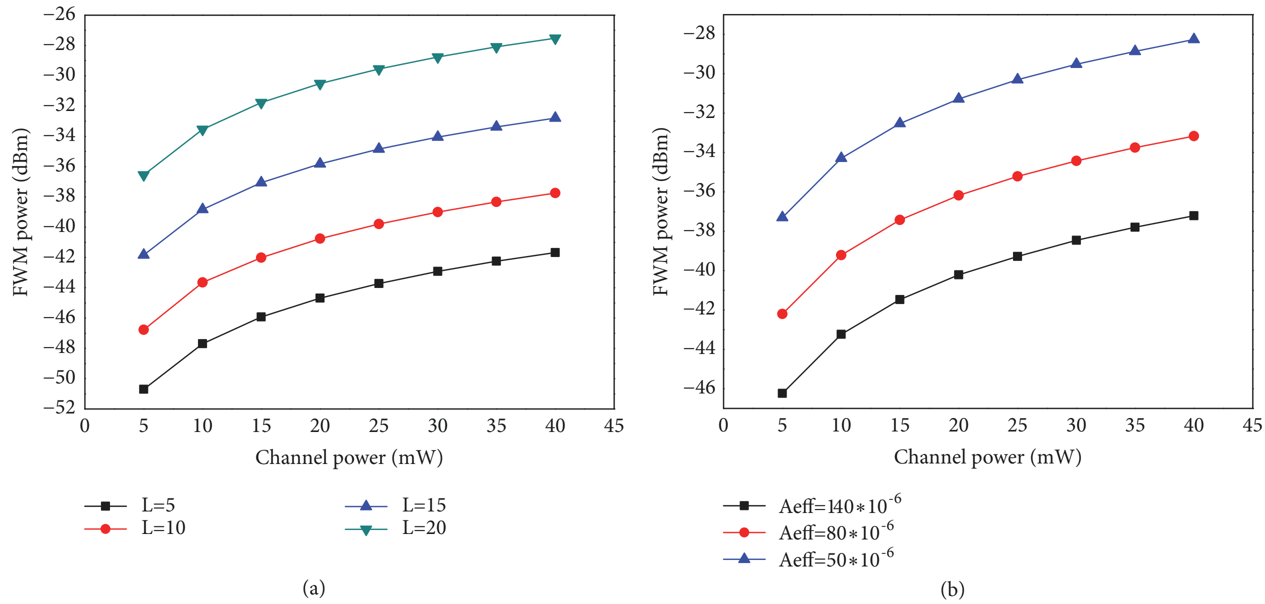

Figure 1: Dependence of FWM crosstalk products over channel power at different values: (a) fiber length (L) and (b) core effective area (A_{eff}).

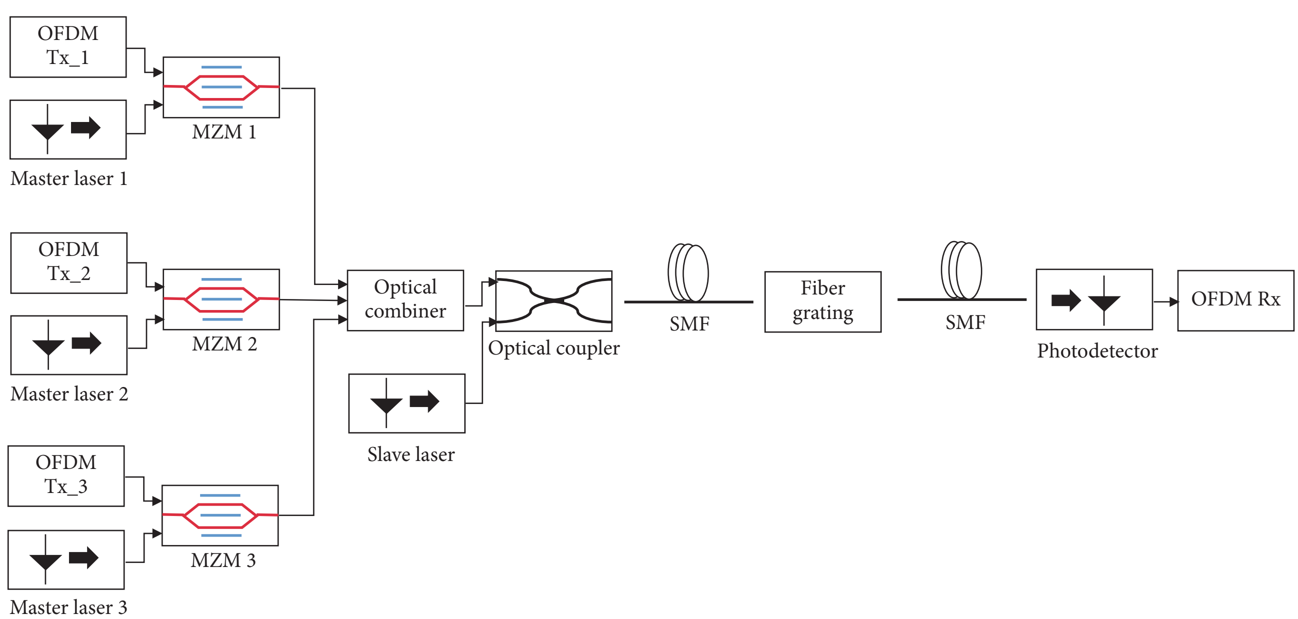

Figure 2: Configuration of 3-channel OFDM-WDM system using master-to-slave injection-locking technique.

shift or bias point. The power transfer characteristics of MZM are good at quadrature bias point for direct-detection systems [18].

The different parameters of OFDM-WDM system are listed in Table 1. Further, to suppress the effect of FWM crosstalk, injection-locking technique is employed. In the proposed technique, we have derived the slave laser at a nearby frequency of master lasers. This injection ratio can be defined as P_{master}/P_{slave}, where P_{master} and P_{slave} are the optical powers in case of master and slave laser, respectively. A comparative analysis of FWM crosstalk generation in optical system is presented in Figure 3. The injection-locking technique offers better performance by lowering the magnitude of FWM products, i.e. ~20 dB reduction in power level of FWM crosstalk products, than that of without injection-locking.

Further, the locking conditions of both (master and slave) lasers affect the system performance. In case of unstable injection-locking, the strong oscillations may appear in the output power caused due to beating in between the components of the optical field. The output power of injection-locking system depends upon the frequency detuning between the free-running slave laser and the injected

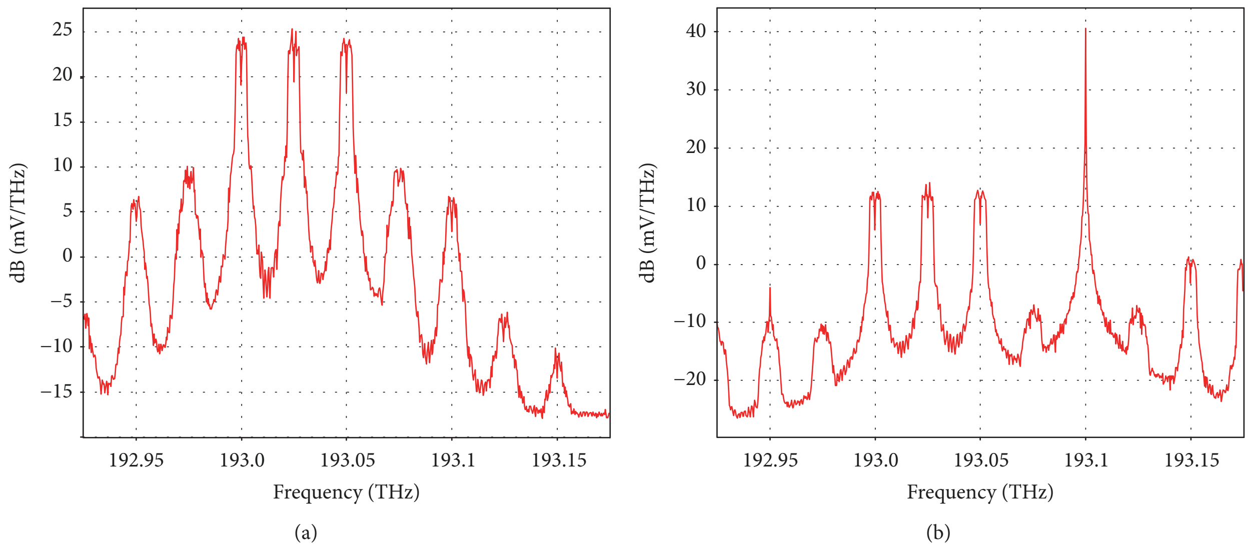

Figure 3: Received optical spectra of OFDM-WDM system (a) without injection-locking and (b) with injection-locking.

Table 1: Different parameters of 3-channel OFDM-WDM system.

Parameters	Value
Data rate	10 Gb/s
OFDM subcarriers	64
Operating wavelength for master laser 1	1553.33 nm
Operating wavelength for master laser 2	1553.13 nm
Operating wavelength for master laser 3	1552.93 nm
Operating wavelength for slave laser	1552.53 nm
Channel spacing	25 GHz
Fiber length	2×100 km
MZM bias point	$\pi/2$

optical beam. The biasing of semiconducting laser in such optical injection can help in locking of optical field components with respect to the current modulation and the optical injection [19]. The bias point should be carefully chosen in order to obtain perfect locking conditions. If the slave laser power is not strong enough to affect the locking conditions, the optical frequencies may operate in FWM regime. Figure 4 shows the variation in distribution of power among FWM cross-products as function of bias current for slave laser. The bias current of slave laser is varied from 8 mA to 40 mA. At high injection ratio, the FWM crosstalk occurs with high power levels and can degrade the system performance. Therefore, without increasing the optical power levels of master lasers, the strength of optical signal from slave laser can be tuned with the help of bias currents [20]. As biasing of slave laser increases from 8 mA to 40 mA, the power level of FWM products decreases significantly (refer to Figures 4(a)–4(f)). However, further increment in bias current of slave laser does not cause any significant reduction in power level of FWM products (refer to Figures 4(g)–4(h)). These variations in power of FWM products near the operating wavelengths of master(s) and slave lasers are plotted in Figure 5. The appropriate dc-biasing of slave laser offers improved modulation characteristics for better locking conditions in order to suppress the FWM products.

From Figure 5, it is clear that a threshold point has been achieved for appropriate biasing of slave laser in order to suppress the FWM products, i.e., 40 mA. The comparative analysis of injection-locking technique is also carried out with respect to existing literature (refer to Table 2).

Therefore, injection-locking technique offers effective suppression of FWM effects and can enhance the system performance by avoiding the complexity of the system.

5. Conclusion

In this paper, we have investigated the fiber nonlinearities, especially FWM. There are several parameters that may contribute to reducing the power level of FWM crosstalk products, i.e., appropriate selection of channel spacing and core effective area. However, significant decrement in FWM crosstalk power levels can be obtained by employing the injection-locking technique, i.e., ~20 dB reduction in power level of FWM crosstalk products. The slave laser should be biased appropriately in order to obtain stable-locking conditions. We have achieved excellent suppression of FWM products at a bias current of 40 mA for slave laser.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Table 2: Critical analysis of the proposed technique with respect to existing literature.

Research work(s)	Proposed mechanism	Outcomes
Bordonalli et al., 2015	Injection-locking technique	Optical comb generation with reduced phase noise spectral density (below -110 dBc/Hz)
Zhu et al., 2017	Combined effect of FWM and injection-locking	Photonic generation of microwave signals
Jignesh et al., 2018	Injection-locking technique	XPM-phase distortion cancellation
Hu et al., 2017	Multiple optical phase conjugation pairs	Fiber nonlinearity mitigation
Proposed work	**Single-stage injection-locking technique**	**Suppression (~20 dB) of power level of FWM crosstalk**

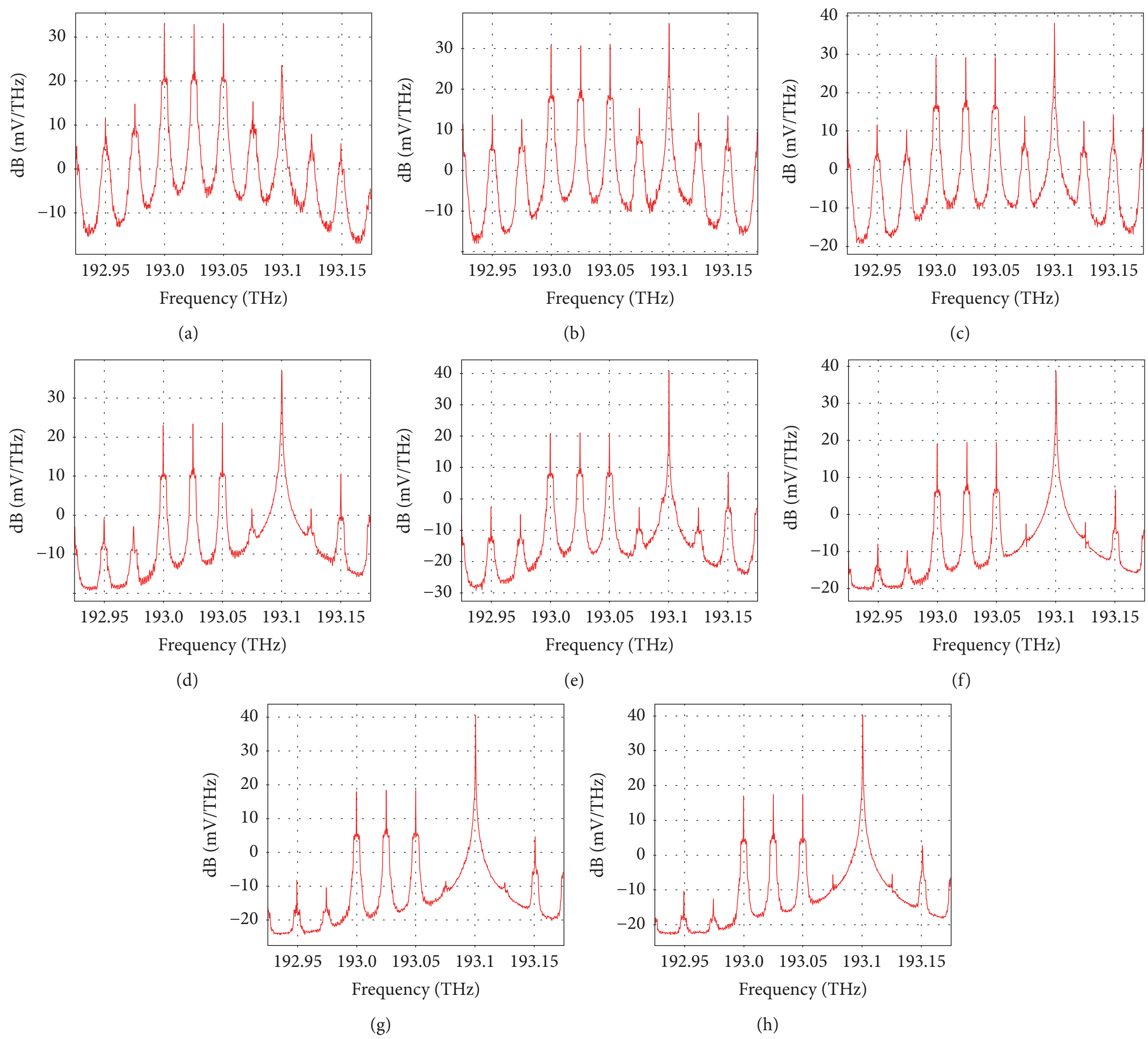

Figure 4: Received optical spectra with significant FWM crosstalk products as a function of bias current of slave laser: (a) 8 mA, (b) 9 mA, (c) 10 mA, (d) 20 mA, (e) 30 mA, (f) 40 mA, (g) 50 mA, and (h) 60 mA.

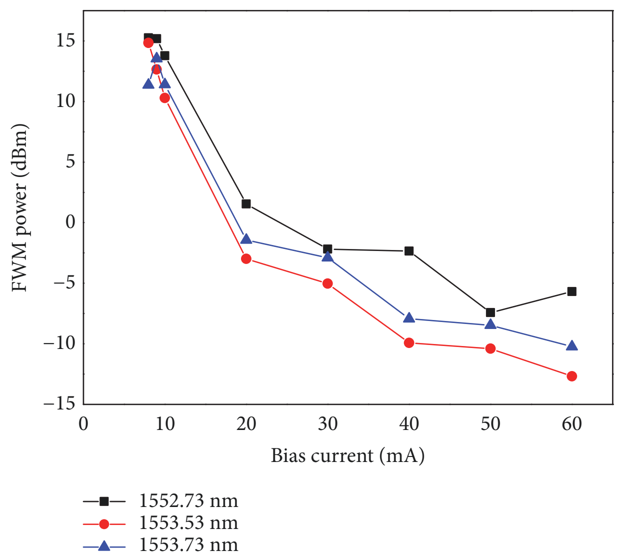

Figure 5: Optical power-to-bias current curves for FWM products near the operating wavelengths of master(s) and slave laser.

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