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Reduction of four-wave-mixing noises in FDM optical fiber transmission systems in unequally spaced frequency allocations using base units

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ABSTRACT

The purpose of this paper is to reduce four-wave-mixing (FWM) noises with narrow total bandwidth in frequency-division-multiplexing optical fiber transmission systems. In this work, unequally spaced (US) frequency allocations using base units (BUs), which have US frequency allocations, are proposed, and dependence of the total bandwidth and FWM noises on the allocation of the BUs is investigated. When the frequency separations of the channels in the BUs are ascending arithmetic progressions, the lowest power penalty is obtained for the combination of the BUs with ascending bandwidths.
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1. Introduction

Four-wave mixing (FWM), which is one of the third-order nonlinear optical effects in the optical fiber, degrades transmission characteristics in frequency-division-multiplexing (FDM) optical fiber transmission systems with low-dispersion optical fibers such as dispersion-shifted fibers (DSFs) [1,2]. The frequency f_{pqr} of FWM light is given by

$$f_{pqr} = f_p + f_q - f_r, \tag{1}$$

where f_p, f_q, and f_r are frequencies of signal light. In equally spaced (ES) frequency allocations where the frequency separations between the adjacent channels are equal, a large number of FWM light waves with the same frequency as the signal light are generated according to Eq. (1). To avoid overlapping of the frequency of the signal light and that of the FWM light, unequally spaced (US) frequency allocations [3–6] have been proposed. However, US frequency allocations have two problems: a large total bandwidth and a complicated procedure to completely avoid overlapping of the frequency of the signal light and that of the FWM light. To obtain a modest total bandwidth with a simple procedure, repeated US (RUS) frequency allocations [7–9], and modified RUSs such as equally spaced RUS (ERUS) and unequally spaced RUS (URUS) frequency allocations [10,11] have been demonstrated. These RUS, ERUS, and URUS frequency allocations use a single base unit (BU), which has US frequency allocation, and have narrower total bandwidths than US and lower FWM light intensities at channel frequencies than ES [7–11]. In URUS frequency allocations with plural BUs [12,13], where the BUs have US frequency allocations different from each other, the total bandwidth has been narrower and the FWM noises have been lower than those in the URUS frequency allocation with a single BU. The dependence of the total bandwidth and the FWM noises on the number of BUs has been also analyzed, and five kinds of BUs have led to the narrowest total bandwidth and the lowest power penalty [13]. In Ref. [13], a group is formed by combining BUs, and the group is repeated to form the URUS frequency allocation. The only exception in Ref. [13] is a group which is formed by combining five kinds of BUs, and this group is not repeated because all channels are accommodated without repeating this group. This group which is formed by combining five kinds of BUs is an US frequency allocation, and showed best transmission characteristics. This result indicates that combining different kinds of BUs might be candidates to form low-noise US frequency allocations with relatively easy procedures.

In this paper, based on a hint in Ref. [13], US frequency allocations using BUs, which have US frequency allocations, are proposed in order to decrease FWM noise further. In order to find appropriate allocations of BUs to form US frequency allocations, dependence of the total bandwidth and FWM noises on the allocation of the BUs is analyzed. It is found that the lowest power penalty is obtained for the combination of the BUs with ascending bandwidths when the frequency separations of the channels in the BUs are ascending arithmetic progressions.

2. Frequency allocations of the base units

Fig. 1 shows BUs with six channels, which are investigated in this paper. In BUm, the frequency separation $\Delta f_{mn}(x)$(GHz)

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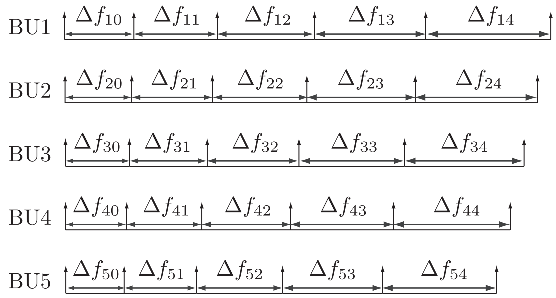

Fig. 1. Investigated base units.

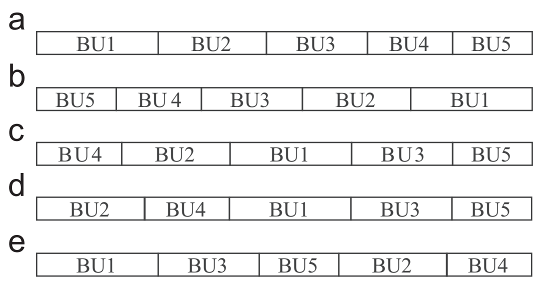

Fig. 2. Investigated allocations of the five base units.

between the channels is an ascending arithmetic progression, which is given by

$$\Delta f_{mn}(x) = 125 - x(m-1) + 25n, \tag{2}$$

where x=2.5, 5.0, 7.5, 10 GHz, m=1, 2, 3, 4, 5, and n=0, 1, 2, 3, 4. Note that all BUs in Fig. 1 have US frequency allocations and BUk is different from BUl for $k \neq l$.

In ITU-T Recommendation G694.1 [14], the dense WDM frequency grid is specified only in ES frequency allocations where the minimum channel spacing is 12.5 GHz. To obtain US frequency allocations, which are arithmetic progressions satisfying the criterion in [5], multiples of the minimum channel spacing of 12.5 GHz are included in Eq. (2) as a trial function. It should be noted that the frequency separation in Eq. (2) is an arithmetic progression when x and m are fixed and satisfies the criterion in [5].

To suppress an increase in the total bandwidth for a large value of m, the frequency separation $\Delta f_{mn}(x)$ includes $-x(m-1)$, which decreases $\Delta f_{mn}(x)$ with an increase in m for a common value of n and $x>0$. In our previous paper [13], x was fixed to 5.0 GHz, and the value of x was not optimized.

Fig. 2 shows allocations of the BUs which are investigated in this paper. The maximum frequency of a BU is the same as the minimum frequency of the following BU. For example, in Fig. 2 (a) the maximum frequency of BU1 is the same as the minimum frequency of BU2, and the maximum frequency of BU2 is the same as the minimum frequency of BU3, and so on. The number of channels is 24 while five BUs can accommodate 26 channels. The zero-dispersion frequency is placed at the center of the total bandwidth which is occupied by 24 channels.

The number of combinations of arranging five BUs is $5! = 120$. Among these combinations, five combinations are selected from the viewpoint of ascending and descending orders of the bandwidth of BUs with an increase in the channel number. In order to form frequency allocations with low FWM noise, aperiodicity in frequencies is important. This reason is that periodicity in frequencies leads to generations of FWM light with the same frequency of signal light; aperiodicity in frequencies leads to generations of FWM light with a different frequency from that of signal light. Therefore, to obtain aperiodicity in frequencies, five BUs are chosen from the viewpoint of ascending and descending orders of frequency spacing in the BUs with an increase in the channel number. This viewpoint is the same as the viewpoint of ascending and descending orders of the bandwidth of BUs with an increase in the channel number. In the following, the allocations of the BUs, which are shown in Fig. 2(a)–(e), are denoted as BU-12345, BU-54321, BU-42135, BU-24135, and BU-13524, respectively. With an increase in the channel number, the bandwidths of the BUs decrease for BU-12345 in Fig. 2(a); the bandwidths of the BUs increase for BU-54321 in Fig. 2(b), the bandwidths of the BUs increase and then decrease for BU-42135 in Fig. 2(c); the bandwidths of the BUs decrease, increase, and then decrease for BU-24135 in Fig. 2(d) and for BU-13524 in Fig. 2(e).

3. Calculations

In our calculations, it is assumed that signal light is intensity modulated by an external modulator to obtain 10 Gb/s NRZ signals. Oscillation wavelengths for light sources are distributed around 1550 nm. A DSF is assumed to have the derivative dispersion coefficient $dD_c/d\lambda$ of 0.07 ps/km/nm^2, the nonlinearity κ of 5.84×10^{-6} m^{-2} W^{-2} [15], the fiber length L of 80 km, and the decay rate α of 0.2 dB/km. It is assumed that signal light is detected by an avalanche photo diode (APD) through a Gaussian optical filter. AWG filters can be used as demultiplexers for unequally spaced signals, even though some transmission channels of the AWG filters may not be used. In this paper, transmission spectra of AWG filters are assumed to be Gaussian, and the optical filters used in this paper are described as Gaussian optical filters. In this paper, signal light is randomly modulated, and the probability of space p_s and the probability of mark p_m are assumed to be $p_s = p_m = 1/2$. A bit error rate (BER) and power penalty are analyzed by the strict approach where probability distribution functions are assumed as Gaussian. In the strict approach [16], the error probability is written as

$$P_e = \frac{1}{2\sqrt{2\pi} C_{IM}^{(s)} \sigma_0^{(s)}} \int_{D/KP_s}^{\infty} d\xi \cdot \int_0^{\infty} d\gamma \exp\left(-\frac{\gamma}{C_{IM}^{(s)}}\right) \exp\left[-\frac{(\xi-\gamma)^2}{2\sigma_0^{(s)2}}\right] + \int_{-\infty}^{D/KP_s} d\xi \int_0^{\infty} d\gamma \exp\left[-\frac{\gamma+1}{C_{IM}^{(m)}}\right] \cdot \frac{1}{2\sqrt{2\pi} C_{IM}^{(m)} \sigma_0^{(m)}} I_0\left(\frac{2\sqrt{\gamma}}{C_{IM}^{(m)}}\right) \exp\left[-\frac{(\xi-\gamma)^2}{2\sigma_0^{(m)2}}\right], \tag{3}$$

where

$$K = \frac{\eta_d e}{hf}, \tag{4}$$

$$N_{th} = \frac{Q_0^2}{4}\left(\frac{KP_{s0}}{Q_0^2} - k\right)^2, \tag{5}$$

$$N_{sh} = kKP_s, \tag{6}$$

$$C_{IM}^{(s)} = \frac{1}{8} \sum_{p \neq q \neq r \neq s} \frac{P_{pqr}}{P_s} + \frac{1}{4} \sum_{p = q \neq r} \frac{P_{ppr}}{P_s}, \tag{7}$$

$$C_{IM}^{(m)} = \frac{1}{8} \sum_{p \neq q \neq r \neq s} \frac{P_{pqr}}{P_s} + \frac{1}{4} \sum_{p \neq q \neq r = s} \frac{P_{pqs}}{P_s} + \frac{1}{4} \sum_{p = q \neq r} \frac{P_{ppr}}{P_s}, \tag{8}$$

$$\sigma_0^{(s)} = \frac{\sigma^{(s2)}}{KP_s} = \frac{\sqrt{N_{th}}}{KP_s}, \tag{9}$$

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