Study on loss and crosstalk in WDM passive optical network based on spectral slicing

Shaofeng Qiu (邱绍峰) and Ge Fan (范 戈)

National Laboratory on Local Fiber-optic Communication Networks & Advanced Optical Communication Systems, Shanghai Jiao Tong University, Shanghai 200030

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A model for calculating loss and crosstalk in WDM passive optical network based on spectral slicing is proposed in this paper. Through theoretical analysis and numerical calculation, the relationship between loss or crosstalk and the parameters of the system, such as the bandwidth of the light-source, the parameters of the multiplexer, the number of channels and the fraction of channel misalignment, was demonstrated.

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WDM passive optical network (PON) is an attractive solution for future broadband access network. It offers potentials of large capacity, network security and data transparency[1].

However, WDM PON can be relatively expensive to implement, owing to the cost of the specified wavelength sources. A well known technology to reduce the cost of WDM system is spectral slicing. Spectral slicing is a WDM technique in which optical filters are used to obtain a spectral slice of light from a broadband source, and modulators encode data onto the slice.

Several experimental systems of WDM PON based on spectral slicing have been reported[2,3] and the upstream transmission path of these systems is illustrated in Fig. 1. The multiplexer has N input ports. Each port has multiple passbands separated from one another by the free spectral range (FSR) of the multiplexer, and the passbands of one port are separated from those of the adjacent ports by the channel spacing (CS) of the multiplexer. Each optical network unit (ONU) contains a broadband source, for example LED. Light from LED is spectrally sliced at the multiplexer, and the signals are multiplexed into the fiber that goes to the optical line terminal (OLT). The OLT contains a demultiplexer that routes the light to the receiver (Rx) array. In the downstream transmission, the effect of spectral slicing need not be considered for the use of multi-wavelength source. So the downstream path is omitted in Fig. 1.

However, spectral slicing has two limitations. One is that the optical loss of spectral slicing is high and the power coupled from a LED into a single mode fiber is limited, so power budget could be a problem. The other is that the interference due to linear crosstalk caused by the tails of Gaussian optical passband can be quite high.

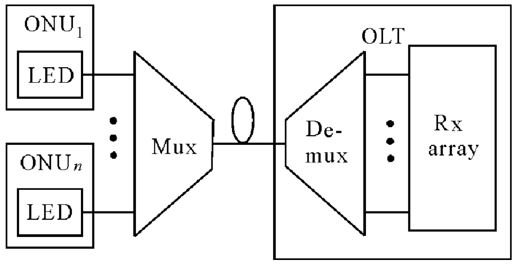

Fig. 1. Structure of the upstream transmission path of WDM PON based on spectral slicing.

Several models for calculating loss and crosstalk in spectral slicing system have been proposed. However, these models only consider one passband of the channel[4,5], or the calculation is complicated[6] and in that the transmission of the multiplexer is treated as Gaussian within ±0.5 channel spacing and constant over the remainder of the FSR. Calculated loss and crosstalk are given in Ref. [6] for channel number $n = 8$ and $n = 16$, and the effects of the parameters of the multiplexer and the fraction of channel misalignment are analyzed. In this paper, we propose a simple model to simplify the calculation and evaluate the effects of the bandwidth of the light-source and the number of channels on both loss and crosstalk in WDM PON based on spectral slicing.

In Fig. 1, we assume that the multiplexer and demultiplexer have the same transfer function, so the spectral slicing loss L can be written in dB as

$$L = -10\log\frac{\int S\cdot M_i d\lambda}{\int S d\lambda}, \qquad (1)$$

and the crosstalk C_i for channel i can be written in dB as

$$C_i = 10\log\frac{N_i}{P_i} = 10\log\frac{\sum\limits_{j\neq i}\int SM_jM_i d\lambda}{\int SM_i d\lambda}, \qquad (2)$$

where S is the incident optical spectrum, namely, the spectral emission of LED in Fig. 1, M_i and M_j is the transmission function for the channel i and j of the multiplexer, P_i is the optical power received at the channel i, and N_i denotes the optical crosstalk noise due to all adjacent channels interfering with the channel i.

Both the spectral emission of LED and the transmission characteristics of multiplexer can usually be described by a Gaussian function[7]. Therefore, for a LED with peak emission wavelength λ_0, and full width at half maximum (FWHM) spectral bandwidth λ_A and a total optical power output P_0, the spectral emission can be written as

$$S = \frac{P_0}{a\sqrt{\pi}}\exp\left(-\frac{(\lambda-\lambda_0)^2}{a^2}\right), \qquad (3)$$

where $a = 0.6\ \lambda_A$. The multiplexer provides multiple passbands per channel, each separated by FSR, so the transmission of the multiplexer is treated as the sum of multiple Gaussian passbands. Therefore the transmission function for channel i of the multiplexer can be written as

$$M_i = \sum_k \exp[-(\lambda - \lambda_{ik})^2/b^2], \tag{4}$$

where $b = 0.6\lambda_B$, $\lambda_{ik} = \lambda_i + k\times\text{FSR}$, λ_B is the FWHM of the multiplexer, and λ_i is the center wavelength of channel i. From Eqs. (1) to (4), we can get

$$L = -10\log\frac{b}{\sqrt{a^2+b^2}} -10\log\sum_k \exp\left[-\frac{(\lambda_0-\lambda_{ik})^2}{a^2+b^2}\right], \tag{5}$$

$$C = -10\log\sqrt{2}\sum_{l=0}^{n/2} \exp\left[-\frac{(\lambda_i-\lambda_{jl})^2}{2b^2} - \frac{(\lambda_0-\lambda_{jl})^2}{2a^2}\right], \tag{6}$$

where $\lambda_{jl} = \lambda_j + l\times$ CS.

Calculated slicing loss are shown in Fig. 2 and Fig. 3. From Fig. 2, it is clear that slicing loss increases with the number of channel n. The relationship between slicing loss and the FWHM of the source is interesting: slicing loss is minimal when the FWHM equals to $n\times$ CS nm. And on the left side of the central wavelength, when the FWHM decreases, slicing loss increases, because the source power intensity decreases rapidly. While on the right side of the central wavelength, slicing loss increases rapidly with FWHM as described in the first item of Eq. (5). Furthermore, FWHM/CS of the multiplexer has effect on slicing loss. The curves in Fig. 3 are figured out for $n = 16$ and the source's FWHM=50 nm, but the results are similar with different n and FWHM. When FWHM/CS increases slicing loss decreases, and increasing of FWHM/CS from 0.5 to 1 will yield a 7 dB improvement in loss, as shown in Fig. 3. So slicing loss can be decreased by choosing a larger FWHM/CS.

Besides slicing loss, crosstalk is another consideration. An eye-closing model[8] shows that the optical power penalty in dB due to linear crosstalk is

$$\Delta P = -10\log\left(1+\frac{1}{C}\right), \tag{7}$$

where the crosstalk C must be at least -7 dB in order to limit the power penalty of 1 dB. At higher crosstalk, the penalty derived from Eq. (7) will rise quickly. If a PON has an optical dynamic range requirement of 20 dB, we should have to achieve a -27 dB crosstalk.

Crosstalk increases with the FWHM/CS, as shown in Fig. 3. The FWHM/CS should be larger than 0.7 in order to achieve the crosstalk less than -27 dB.

In a WDM PON system, the spectral characteristics of the multiplexer change when it is subjected to large temperature excursion. This would result in channel misalignment between multiplexer and demultiplexer, and cause extra crosstalk. When consider the effect of channel misalignment, λ_{jl} in Eq. (6) should be expressed as $\lambda_{jl} = \lambda_j - f\times$ CS $+l\times$ CS, where f denotes the fraction of channel misalignment. The relationship between the crosstalk and the fraction of channel misalignment for $n = 16$ and different FWHM/CS are shown in Fig. 4.

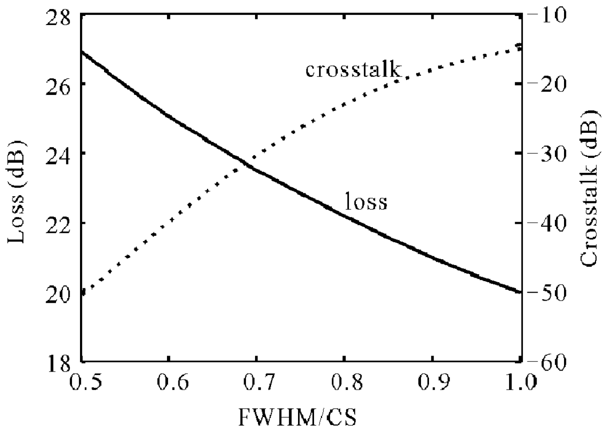

Fig. 3. Slicing crosstalk as a function of the FWHM/CS of the multiplexer.

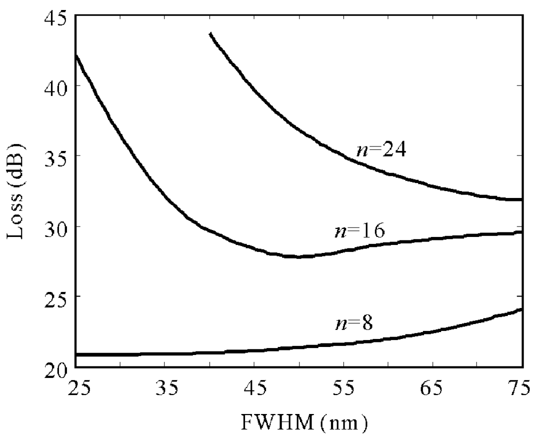

Fig. 2. Slicing loss vs FWHM of the source for channel number $n = 8$, $n = 16$ and $n = 24$.

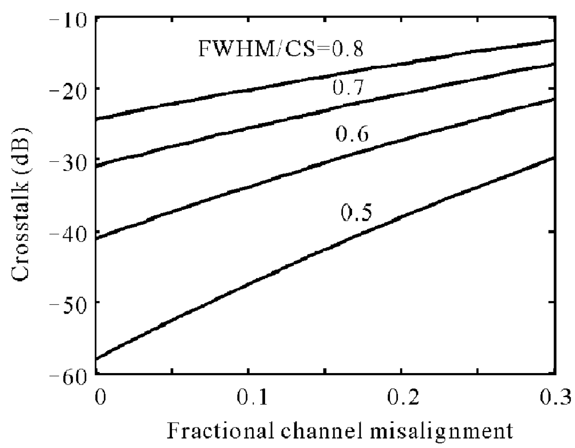

Fig. 4. Crosstalk vs the fraction of channel misalignment.

Crosstalk increases with f and the effect is stronger at lower FWHM/CS. For FWHM/CS=0.6, when $f = 0.2$, crosstalk is -27.3 dB and when $f = 0.3$ crosstalk increases to -21.6 dB.

In this paper, we propose a model for calculating loss and crosstalk in WDM passive optical network based on spectral slicing. Through theoretical analysis and numerical calculation, the relationship between slicing loss and the FWHM of the source, the number of channels and FWHM/CS of the multiplexer, the effect of FWHM/CS and the fraction of channel misalignment on crosstalk, are derived and analyzed. The results show that slicing loss is minimal when the FWHM of the source equals to $n\times$ CS for a given CS. However, crosstalk increases with FWHM/CS. So it should consider both loss and crosstalk to choose FWHM/CS. Additionally, channel misalignment has effect on crosstalk, so it is necessary to apply wavelength trace technique to reduce channel misalignment.

S. Qiu's e-mail address is qsf@mail.stju.edu.cn.

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