Cascadability of Passband-Flattened Arrayed Waveguide-Grating Filters in WDM Optical Networks

T. Otani, N. Antoniades, I. Roudas, and T. E. Stern

***Abstract*— The cascadability of passband-flattened arrayed waveguide-grating (AWG) filters is studied using experimental and theoretical transfer functions. The formalism is general and can be used to cascade any type of filter at any channel spacing. For example, modeling indicates that transmission through 100 such AWG (de)multiplexers at 200-GHz channel spacing, assuming 10-Gb/s data streams introduces distortion-induced penalties below the widely acceptable 0.3-dB limit, provided that certain filter design requirements are satisfied. All simulations focus on the filter cascadability and central frequency misalignment effects, and neglect nonlinearities and crosstalk.**

***Index Terms*—Arrayed waveguide grating (AWG) filter, filter cascadability, frequency misalignment, WDM optical networks.**

I. Introduction

WAVELENGTH-DIVISION-MULTIPLEXED (WDM) optical networks of the near future can potentially include a significant number of optical filters, e.g., optical (de)multiplexers (MUX/DMUX's) [1]. Filter concatenation will make the effective passband of the cascade narrower due to the passband curvature and ripple of the individual filter transfer functions. In addition, filter and laser central frequency misalignments will further reduce the bandwidth of the filter cascade. All the above will give rise to signal waveform distortion [2] which can lead to eye-closure and can introduce significant network performance degradations. The above impairment can impose strict requirements on the filter/laser allowable misalignments, affect the filter selection criteria for networks and limit the number of optical nodes that can be cascaded. Although the feasibility of large scale all-optical WDM networks where a large number of optical filters can be found is still under debate [3], it is nevertheless of great importance to know the exact number of filters that a signal can go through and the effects on its performance.

The cascadability of multilayer interference (MI) filters as well as Fabry–Perot (FP) filters has been investigated using simulation models in [2] and [4]. It was shown that MI filters are likely candidates for MUX's/DMUX's in national scale optical networks. Arrayed waveguide-grating (AWG) filters, on the other hand, can not only demultiplex very dense WDM signals, but can be effectively utilized as all-optical wavelength routers. However, unlike MI filters, AWG filters are susceptible to cascading due to their round transfer functions [5]. One method for flattening their passband is presented in [6].

Our work focuses on determining the cascadability of such passband-flattened AWG filters assuming 200-GHz channel spacing. A realistic and easily extendable to any type of filter simulation study of the filter-induced distortion based on experimental data as well as an analytical model for the individual transfer functions is presented. Laser/filter misalignment tolerances are obtained by studying their effect on the 3-dB bandwidth of the optical filter cascades. We show that passband-flattened AWG filters are good candidates for national scale networks, provided that certain requirements on their passband flatness, ripple and bandwidth are satisfied. On the other hand, the results on 100-GHz spacing round-passband AWG's indicate that such devices are extremely susceptible to cascading and can not be used for such applications.

II. Cascadability of Realistic AWG Filters

Measurements of 16 transfer functions of a set of a commercial passband-flattened AWG wavelength router are conducted. This is the 200-GHz spacing device with the transfer functions of each individual channel of the AWG router having a slightly different shape and centered at a slightly different frequency. Their central frequency offsets from their channel nominal frequencies vary in the range [-10 GHz, $+14$ GHz]. The average of their 3-dB bandwidths (defined as 3-dB down from the minimum transmission point) is 129 GHz with a standard deviation of only 2 GHz. Assuming that the transfer functions of all AWG channels are independent, we calculate the *generalized geometric mean* transfer function as the Mth root of the product of all M measured transfer functions [4]. The *generalized geometric mean* is a random function that for large M represents a typical value of the transfer function for each individual filter. The equivalent transfer function for the entire filter cascade (N filters) is assumed to be the Nth power of the *generalized geometric mean* transfer function.

Fig. 1 shows the equivalent transfer functions for cascades of 10, 50, and 100 filters based on the measured AWG filter

Manuscript received May 20, 1999; revised August 5, 1999.

T. Otani was with the Electrical Engineering Department, Columbia University, New York, NY 10027-4712 USA. He is now with the KDD R&D Laboratories, Saitama 356-8502, Japan.

N. Antoniades and I. Roudas were with the Electrical Engineering Department, Columbia University, New York, NY 10027-4712 USA. They are now with Corning Inc., Somerset, NJ 08873 USA.

T. E. Stern is with the Electrical Engineering Department, Columbia University, New York, NY 10027-4712 USA.

Publisher Item Identifier S 1041-1135(99)08667-X.

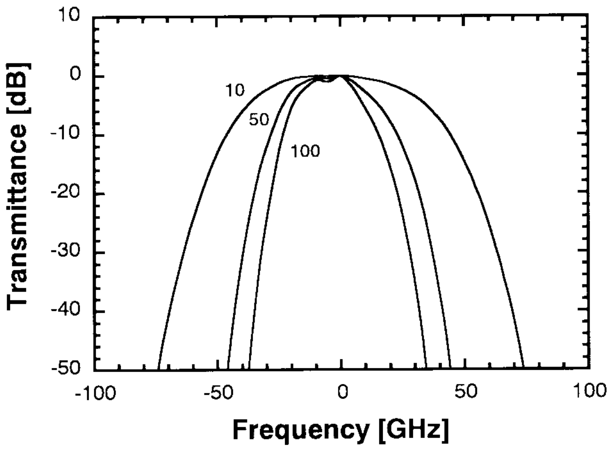

Fig. 1. Equivalent transfer functions for cascades of 10, 50, and 100 passband-flattened AWG filters based on experimental data, and including filter random misalignments.

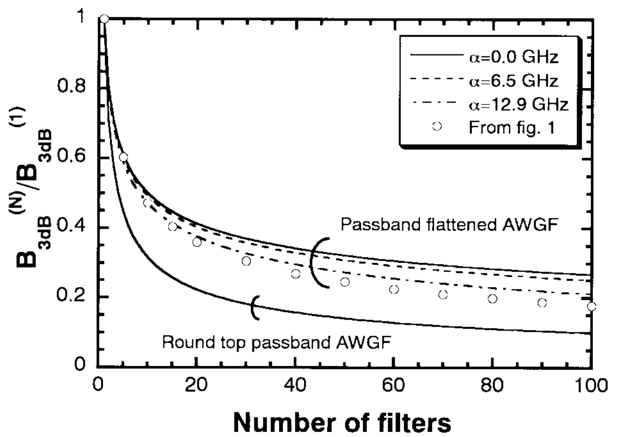

Fig. 2. Normalized 3-dB bandwidth of the equivalent transfer function of passband-flattened AWG filters (dotted lines) versus number of cascaded filters for different uniform central frequency laser misalignments (α) as well as experimental data from measured filters (individual points). Also included is the corresponding curve for round-passband AWG's (solid curve) obtained by fitting a single Gaussian curve on measured data.

data and the calculated geometric mean approach. We observe that the 3-dB bandwidth of the cascade of 100 filters is now reduced to about 25 GHz. There appears to be passband ripple near the central nominal frequency, which is rather small (of the order of 2 dB). However, the ripple effect is systematic inducing an asymmetric passband for the equivalent transfer function of the cascade.

A simplified theoretical study of the cascadability can be done as follows: the transfer function of the passband-flattened AWG filters is approximated by a combination of two Gaussian functions [6] with different 3-dB bandwidths which are offset from each other for best fit. Such an approximation is shown to fit well the measured transfer functions. Assuming a uniform distribution of the filter central frequency offsets α in the range $[-\alpha, +\alpha]$ where α is a positive constant, an analytical relationship can be derived describing the effect of bandwidth narrowing as a function of the number of cascaded filters and the maximum allowable filter central frequency offsets α. Fig. 2 shows the effect of bandwidth narrowing as a function of the number of cascaded filters N. The 3-dB bandwidth $B_{3\,\mathrm{dB}}^{(N)}$ after N filters is normalized by that of one filter, $B_{3\,\mathrm{dB}}^{(1)}$. The solid and dotted lines describe the above analytical model for different maximum allowable central frequency offsets. We observe that filter misalignments introduce an additional narrowing of the passband. The individual points are experimental data obtained from Fig. 1. The specific measured filters exhibited very small central frequency misalignments of about 2.5 GHz and their transfer functions were highly asymmetric. As a result of mainly this asymmetry, the analytical model and the experimental data differ as shown in Fig. 2. For comparison, the round-passband (nonflattened, used for 100-GHz spacing systems) AWG filter curve is also included in Fig. 2. It is clear that these filters are very susceptible to cascading since their 3-dB bandwidth is reduced to less than 10% of its original value after 100 filters. Fig. 3 presents contours of the 3-dB bandwidth of the overall filter cascade of the passband-flattened AWG's as a function of the number of cascaded filters and the filter nominal central frequency misalignments. The contours are computed using the analytical filter model, and provide us with some useful insight for the

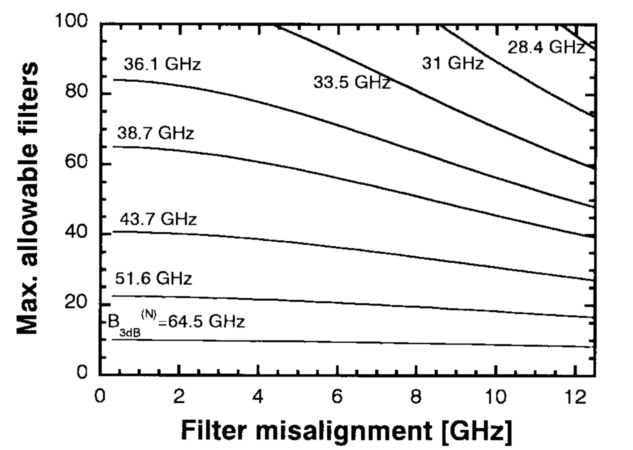

Fig. 3. Contour plots of the 3-dB bandwidth of the equivalent transfer function for cascades of passband-flattened AWG filters as a function of the number of filters and filter uniform central frequency misalignments (α).

selection process of optical filters. For example, if the central frequency offsets of our manufactured filters are within the [−12.5 GHz, +12.5 GHz] region, the 3-dB bandwidth of a cascade of 100 such AWG filters will be reduced to about 20%, compared to the individual filter 3-dB bandwidth. It is thus clear based on Fig. 3 that passband-flattened AWG filters are less susceptible to cascading than their round-passband AWG counterparts but are more susceptible to filter/laser misalignments which must be tightly controlled to avoid the steep parts of the curves of Fig. 3.

III. Calculation of System Penalty

We now calculate the intersymbol interference (ISI) on the signal at the receiver, which is caused by the amplitude and phase distortion introduced by filter cascading and laser/filter misalignments using an in-house developed simulation tool. Externally modulated lasers with zero chirp are assumed, the signal waveform at the output of the transmitter follows a perfect ASK modulation, the bit rate is 10 Gb/s, the bit sequence of “0 111 101 011 001 000” is sent, and a third order Butterworth lowpass filter with cutoff frequency 6.5 GHz

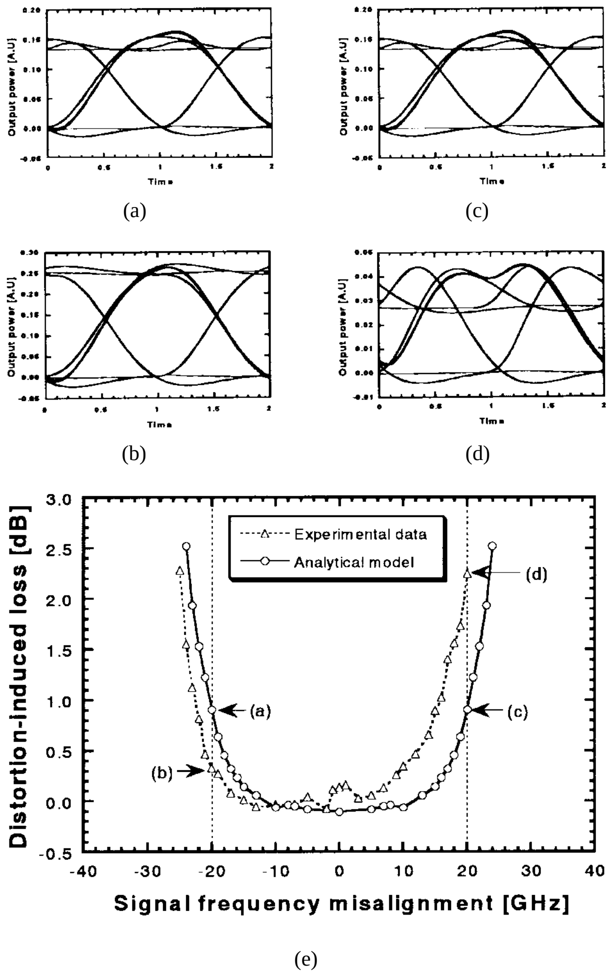

Fig. 4. (a)–(d) Calculated eye-diagrams and (e) distortion-induced loss versus laser misalignment for a cascade of 100 passband-flattened AWG filters based on experimental data as well as the analytical model. Eye-diagrams are at: (a) -20 GHz; (c) $+20$-GHz laser frequency misalignments for the analytical model and at: (b) -20 GHz; (d) $+20$ GHz for the experimental data. Externally modulated lasers with zero chirp are assumed.

is used at the receiver. Since the purpose of this paper is to study the distortion due uniquely to filtering, fiber dispersion, nonlinear effects, and crosstalk are neglected. For our case due to the 200-GHz channel spacing, crosstalk was shown to induce negligible penalty, however depending on the channel spacing and component crosstalk performance it can potentially place significant constraints on the network size. Bandwidth reduction and laser misalignment cause signal attenuation (excess loss) and waveform distortion (distortion-induced loss). Excess loss can be compensated by using optical amplifiers whereas distortion-induced loss causes eye-closure and thus penalty in the network performance that can not be compensated [2]. Fig. 4 shows the distortion-induced loss versus laser frequency misalignment after a cascade of 100 filters. The analytical curves are derived assuming uniformly distributed filter central frequency offsets in the range [-12.9 GHz, $+12.9$ GHz]. Adopting the widely used 0.3 dB as the maximum allowable distortion-induced penalty [2], laser misalignment tolerances of ± 16 GHz are obtained for the analytical case and $-19/+9$ GHz for the experimental one. Results derived using the measured transfer functions (experiment) indicate that the actual filters are in general asymmetric, exhibit passband ripple, and have different laser misalignment tolerances than the analytically modeled ones. Included in Fig. 4 are the eye diagrams for laser misalignments of ± 20 GHz for both the experimental as well as the theoretical data. For the former, the eye-diagrams in both cases are attenuated and distorted but are not the same for the $+20$-GHz and the -20-GHz laser misalignments due to the exhibited asymmetry in the filter transfer functions. On the other hand, the eye-diagrams corresponding to the theoretical transfer functions are symmetric.

IV. Conclusion

The cascadability of passband-flattened AWG filters was studied based on measurements as well as an analytical model for the individual transfer functions. The work was motivated by the need to calculate the signal wavelength distortion that is introduced when the signal propagates through cascades of optical filters whose nominal central frequencies can naturally vary because of manufacturing defects, aging or temperature variations. It was shown that a cascade of 100 passband-flattened AWG filters is, in principle, possible provided that laser/filter misalignments are maintained within some range, filter transfer functions are symmetric about the central frequency and exhibit minimum passband loss. Asymmetric filter characteristics along with passband ripple lead to additional bandwidth narrowing of the equivalent transfer functions of the filter cascades and introduce unwanted distortion-induced loss. Our formalism is very general and can be also used for studying cascadability of passband-flattened AWG's used in 100-GHz spacing systems as opposed to the 200-GHz spacing systems presented in this work [1]. It must be noted that since our study focused exclusively on the effects of cascading a large number of AWG filters, it did not include important effects such as fiber dispersion, fiber nonlinearity and crosstalk. Different signal waveforms, including chirped waveforms, will also be addressed in a future study.

References

[1] R. Wagner, R. C. Alferness, A. A. M. Saleh, and M. S. Goodman, “MONET: Multiwavelength optical networking,” *J. Lightwave Technol.*, vol. 14, pp. 1549–1555, June 1996.

[2] N. N. Khrais, A. F. Elrefaie, R. E. Wagner, and S. Ahmed, “Performance degradation of multiwavelength optical networks due to laser and (de)multiplexer misalignment,” *IEEE Photon. Technol. Lett.*, vol. 7, pp. 1348–1350, Nov. 1995.

[3] R. W. Tkach, E. L. Goldstein, J. A. Nagel, and J. A. Strand, “Fundamental limits of optical transparency,” in *1998 Optical Fiber Communication Conf. (OFC'98)*, pp. 161–162, paper WJ1.

[4] I. Roudas, N. Antoniades, R. E. Wagner, S. F. Habiby, and T. E. Stern, “Influence of filtered ASE noise and optical filter shape on the performance of a WADM cascade,” in *23rd Eur. Conf. Optical Communications (ECOC'97)*, 1997, pp. 143–146, paper TU3.

[5] C. Casper, H. M. Foisel, R. Freund, U. Kruger, and B. Strebel, “Cascadability of arrayed waveguide grating (de)multiplexers in transparent optical networks,” in *Optical Fiber Communication Conf. 1997 (OFC'97)*, pp. 19–20, paper TuE2.

[6] J. B. D. Soole, M. R. Amersfoort, H. P. Leblanc, N. C. Andreadakis, A. Rajhel, C. Caneau, R. Bhat, M. A. Koza, C. Youtsey, and I. Adeside, “Use of multimode interference couplers to broaden the passband of wavelength-dispersive integrated WDM filters,” *IEEE Photon. Technol. Lett.*, vol. 8, pp. 1340–1342, Oct. 1996.