ENGINEERING THE PERFORMANCE OF DWDM METRO NETWORKS

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I. Introduction

The last two years have marked the introduction of DWDM in metro applications. The unique characteristics of the metro environment such as high sensitivity to price due to the fact that cost is shared among a small number of customers (as opposed to a backbone network), the relative abundance of existing fiber as well as the immaturity of the technology have been its main obstacles to widespread deployment to date. Several research projects such as Optical Networks Technology Consortium (ONTC) [1], Multiwavelength Optical NETworking (MONET) [2] and All-Optical Network (AON) [3] had previously focused on applying DWDM in the metro environment. The increasing demand for more bandwidth created by the need for enhanced services mainly through the Internet, and the availability of optical components at the competitive price are now beginning to shift the above network prototypes from the research labs to the field signaling the rise of DWDM in the metro environment [4]. Traditionally most of the network functionality (e.g. signal add/drop, performance monitoring and cross-connecting) has been provided electronically which results in extensive optical to electronic and electronic to optical conversions (O-E-O) at each node in the network (opaque network designs). This scenario is likely to change as optical components are used to route wavelengths transparently (no O-E-Os in the optical path) through the network reducing cost and providing extensive flexibility in combining different protocols and bit-rates. WDM provides the required transparency that appears to be important especially for the multi-vendor metropolitan environments.

We use computer simulation and a combination of single-impairment models as tools to help us identify and understand critical impairments, their relative magnitude in relation to the different network topologies used and to guide the selection of enabling technologies for low cost metro optical transparent network solutions. Performance impairments such as non-linear effects, crosstalk, dispersion/chirp, distortion-induced penalty due to filter concatenation and component ripple are identified, their individual impact on the network performance is studied and mitigation techniques are considered. For example, accumulated ripple can be a serious limitation in networks with a large number of optical components. We show that power equalization will play a fundamental role in achieving the required performance in such applications. In particular, dynamic power equalizers based on liquid crystal technology [5] are very promising candidates compared to traditional Variable Optical Attenuators (VOAs) mainly due to cost issues. Another impairment, the interaction of laser chirp with the fiber dispersion will become increasingly important as transmission distances in metro networks exceed 200 km. At such distances, this will be a major impairment if low cost Directly Modulated Lasers (DMLs) and standard Single Mode Fiber (SMF) is used. The use of Dispersion Compensating Modules (DCMs) with the associated cost and performance issues can be avoided by using a Negative Dispersion Fiber (NDF) such as MetroCor ™ fiber [6].

II. Simulation Case Study

In traditional opaque metro networks, the fiber spans are short, the available power levels are limited to the transmitter's output power and the number of optical components traversed by a signal is small. Therefore, a relatively simple design philosophy can be applied to achieve the performance required for an optical link system. In contrast, in order to engineer transparent networks, effects such as Amplified Spontaneous Emission (ASE) accumulation and channel power deviation caused by amplifiers, optical crosstalk, fiber non-linearities, chirp/dispersion and finally waveform distortion induced by filter bandpass narrowing have to be taken into account. We use a simulation case study to focus on the above impairments in an effort to understand how to better engineer the performance of metro DWDM optical networks. Our network simulation is based on the following two steps: during the first step, the network is decomposed into selected optical paths. The idea is to identify impairments and the corresponding worst-case paths for each impairment. We then focus on the path that can potentially be the worst for most or all the impairments. The second step consists in constructing the point-to-point link that corresponds to the worst-case path, and using an optical link simulation tool to determine the Q-factor for each channel in the path. The Q-factor is defined in [7] and is related to the Bit Error Rate (BER) by the expression:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{e^{\frac{-Q^2}{2}}}{Q\sqrt{2\pi}} \qquad (1)$$

The Q penalty of the system is often expressed in dBs and since we are mostly concerned with the optical penalties introduced by the different impairments, we will use the following definition for dBQs throughout this paper:

$$dBQ = 10\log(Q_{linear}) \qquad (2)$$

Figure 1 presents the architecture of our metro network simulation case study which consists of optical network elements arranged into two interconnected rings that can serve metropolitan applications. Each ring is formed by six bi-directional Wavelength Add/Drop Multiplexers (WADMs) connected with duplex fiber links (working and protection). Cross-connects (XC) #3 and 11 in Fig. 1 are used to provide dynamic wavelength routing and protection between the two rings. Network elements #8 and 14 are WADMs that can be used to drop channels for hand-off to other distribution networks like bus or tree networks. Traditional designs for the WADMs and XCs are shown in Figs. 2 (a-b).

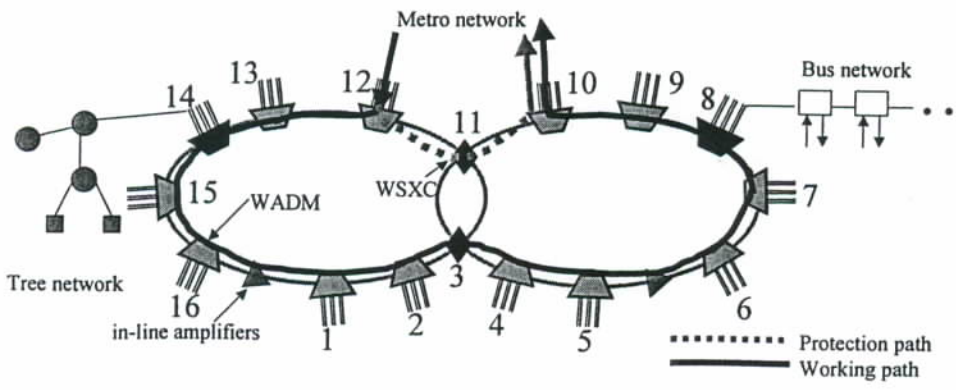

Fig 1: Simulation case study with a worst-case path in an all-optical interconnected ring network.

Amplifiers may be used at crossconnect points, at add/drop nodes or as in-lines to compensate for component and fiber losses. The worst-case path shown in Fig. 1 has a length of approximately 240km (which is typical for the metro environment) and traverses a large number of optical components. All fiber links are assumed equal in length (15 km). Sixteen channels equally spaced at 200 GHz are used in the network and their routing is assumed arbitrary with all channels present on all the links.

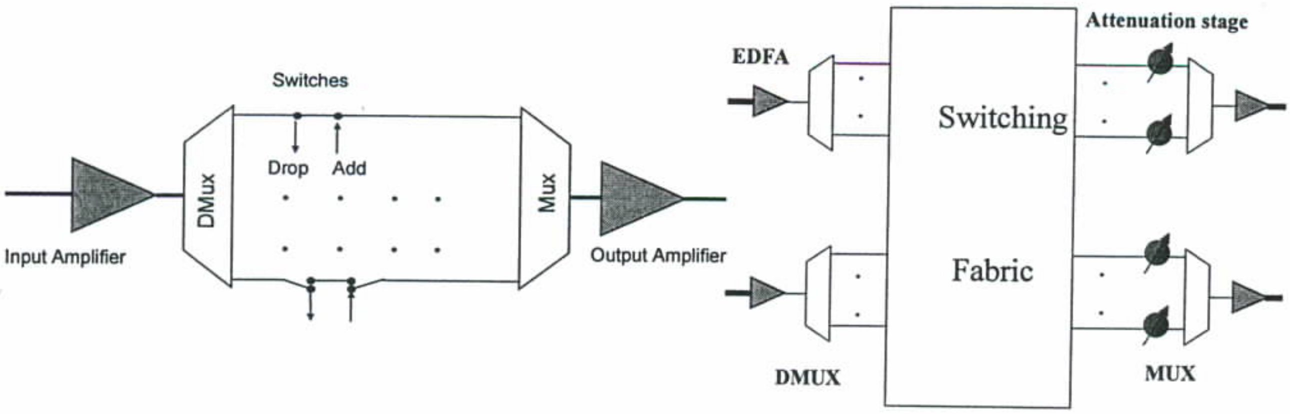

Fig 2: (a) Traditional parallel Wavelength Add-Drop Multiplexer (WADM) configuration; (b) 2 x 2 general Wavelength Selective Cross-connect (WSXC) configuration.

III. Performance Impairments – Mitigation Techniques

(a) Non-linear effects

Our simulations show that for moderate channel launch powers (i.e. up to 5dBm/channel), channel spacing of 200 GHz and 2.5 Gbps bit rates fiber non-linearities will not be a major issue for the case study of Fig. 1. However, in [8] it was shown that for channel spacings of 100 GHz or less there can be metro architectures similar to that of Fig. 1 where for long paths non-linear effects can become important. For these paths the span launched power per channel should be reduced to minimize non-linear effects on the strongest channels. However, the weakest channels might then be affected by the receiver electrical noise since their power will be reduced. Simulation can be used to properly engineer these paths by balancing the effects of receiver electrical noise and fiber non-linearities [8].

(b) Power Divergence

The presence of *strong* and *weak* channels in the network (ie. channel power divergence) is due to the ripple introduced by each component in the network which accumulates as channels propagate through the optical path. The impact of this effect on the network performance will depend on the control scheme used in each of the amplifiers. Moreover, power divergence will impose strict dynamic range requirements on the optical receivers. Figure 3 presents results based on the Q-factor for the worst-case path of Fig. 1 for the strongest and the weakest channels as a function of power divergence assuming fixed gain amplifiers. As the strongest and the weakest channels propagate through the optical components their optical powers diverge and their performance in terms of the Q-factor differs dramatically. The result clearly demonstrates that without the use of dynamic power equalizers in the network the weakest channels are not able to achieve acceptable performance ($Q \geq 8.47$ dB or BER $\leq 10^{-12}$) even for a small channel power variation in the network (~3dB). Included in Fig. 3 is the result assuming the use of dynamic power equalizers at XCs 3, 11 as well as at network elements 8 and 14. As a result, all channels achieve performance better than the one required (Q >= 8.47 dB) and in addition a 0.5 dBQ margin is obtained. In particular, the use of dynamic power equalizers based on liquid crystal technology [5] at the equalization sites provides the combined functionality of switching and/or power equalization all within a single device. The recently introduced Wavelength Selective Switch™ provides these functionalities and if both the switching and equalization properties are used simultaneously then these devices can be used in place of WADMs at specific points in the network of Fig. 1 and the equalization is not needed within the XCs.

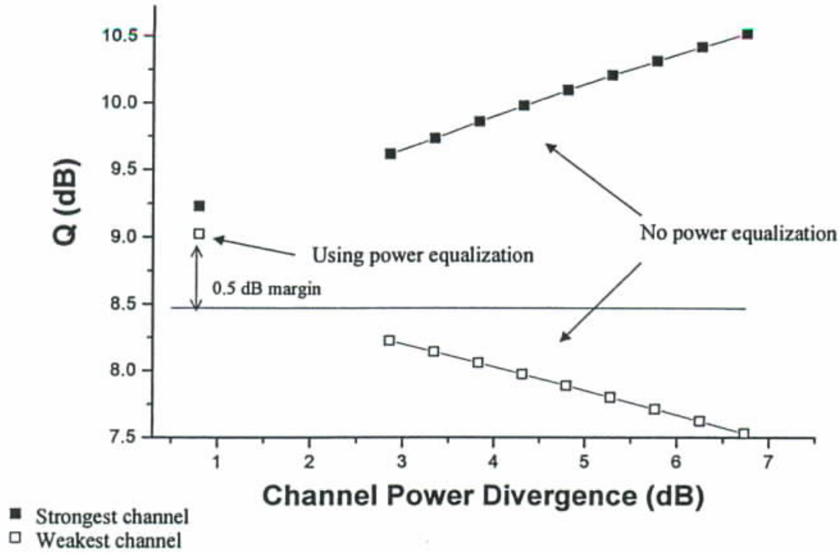

Fig 3: Simulation results of Q-parameter (dB) v.s. channel power divergence (dB) (power level difference between strongest and weakest channels) for the worst-case path of Fig. 1 at 2.5 Gbps.

This results in significant cost and space savings compared to the use of conventional VOAs which would be required for each wavelength.

(c) Chirp/Dispersion

In Fig. 3 Q-factor results have been obtained without taking into account chirp/dispersion effects. At such distance (240 km) and at 2.5 Gbps, fiber dispersion is the major impairment if low cost DMLs and SMF fiber is used. In the cost sensitive metro environment there is a clear tradeoff between reach and cost. Using low cost DMLs will thus require dispersion compensation to achieve the necessary reach. For example, if DML transmitters with 1800 ps/nm rating are used the 0.5 dBQ margin shown in Fig. 3 will provide for a maximum reach of approximately 25 km. However, the remaining 215 km of the worst-case path of Fig. 1 need to be dispersion compensated. Applying dispersion compensation in optical networks, unlike point-to-point systems, is a rather complex task due to the nature and length variability of the optical paths. Moreover, the use of Dispersion Compensating Modules will add an additional deterioration on the Optical Signal to Noise Ratio (OSNR) of all the channels which will be more deleterious for the case of OSNR-limited 10 Gbps networks. In [6], experimental and theoretical results are presented to demonstrate how Negative Dispersion Fibers (NDFs) benefit transmission using OC-48 DMLs as well as OC-192 DML/EA cases. In particular, MetroCor ™ fiber, an NDF, has proven very effective due to its low absolute dispersion values, and more importantly the beneficial interplay of negative dispersion with the positive chirp from the DMLs [9]. Fig. 4 shows the measured Q-factor performance for uncompensated reach of 300 km over MetroCor ™ fiber with 32 OC-48 DMLs. A Q better than 9dB was achieved for all channels. For the same conditions the transmission performance over SMF was significantly degraded and none of the channels achieved the required performance. In the case of MetroCor ™ fiber, negative dispersion/chirp power penalty was obtained indicating performance improvement [6]. Use of NDFs will thus significantly extend the reach of optical paths and enable metro networks such as that of Fig. 1.

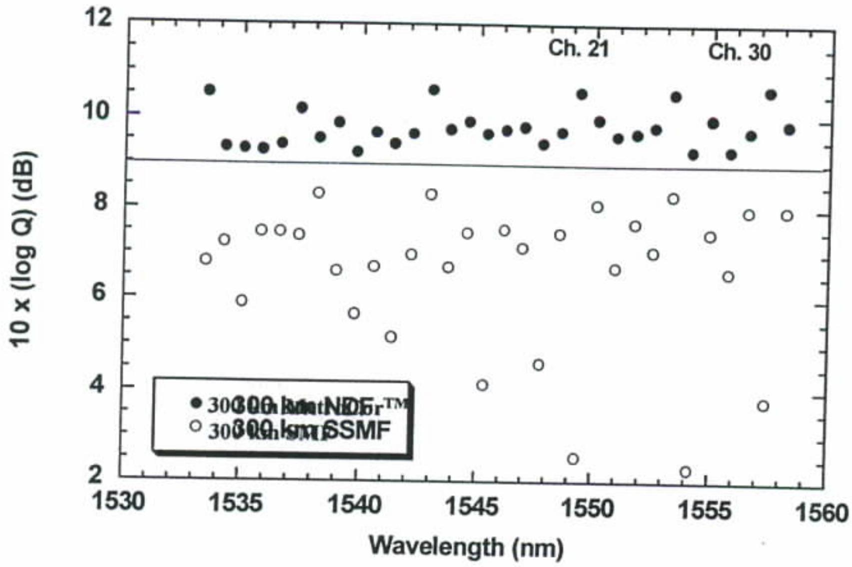

Fig. 4: Q-factor comparison of 32 OC-48 DMLs over 300 km of MetroCor™ fiber and standard single mode fiber (courtesy of [6]).

(d) Filter Concatenation

A potentially serious signal impairment that is unique to optically transparent networks in comparison to opaque networks is distortion-induced eye closure due to signal passage through multiple optical filters between the source and receiver. This effect is essentially non-existent in a point-to-point optical system as a given signal passes through at most 2 filters: a MUX and a DMUX. However, in a transparent optical network, a signal may be demultiplexed and re-multiplexed at many optical cross-connect elements throughout its path before it is finally received. Thus the signal experiences the concatenation of the entire set of filters in its path. The effective spectral transfer function of the filter set is the multiplication of each of the individual filters, and it can therefore be much narrower in spectral width than a single filter [10]. Figure 5 presents this effect using cascades of 1, 4 and 28 filters for a 200 GHz spacing system. The filters are modeled as 3rd order Butterworth in amplitude and their phase is ignored [11]. A reduction in 3dB bandwidth of almost 50 % is observed for the cascade of 28 filters as opposed to only 25% for the 4 filters. Such spectral narrowing of the transfer function is further accelerated by any misalignments in center frequency of the filters traversed by the signal. If the laser is offset from the passband center of the effective filter transfer function, then part of the signal spectrum will experience different attenuation than the rest of the spectrum as the signal gets too close to one of the sidebands of the filter transfer function [10]. This in turn leads to a time-domain distortion (waveform distortion) and a distortion-induced eye closure penalty that is related to a Q penalty. The above effect also introduces excess loss in addition to the vendor-specified insertion loss which is usually specified at the center of the filter passband, however this effect, unlike the distortion-induced eye-closure can be corrected with increased amplification. In the network of Fig. 1 the channel following the worst-case path can potentially traverse at least 4 optical filters if it is only demuxed/muxed once (through XC 3) or a maximum of 28 filters if all WADMs along the way follow the design of

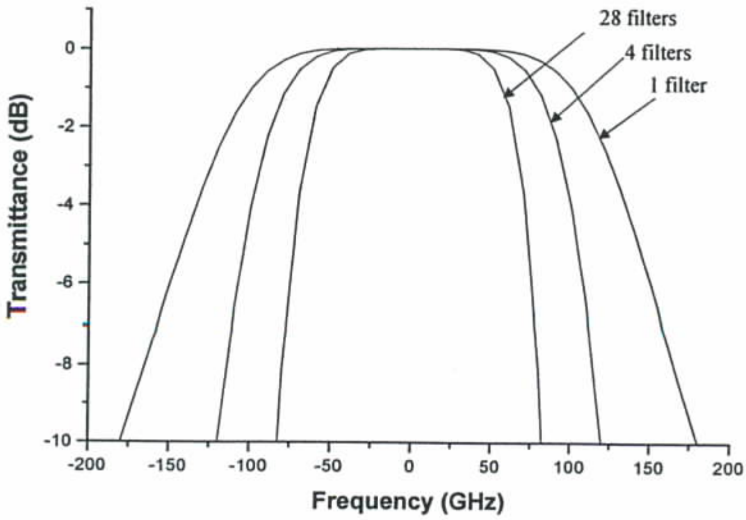

Fig. 5: Passband narrowing effect due to optical filter cascading for 1, 4 and 28 filters whose amplitude is modeled as 3rd order Butterworth.

Fig. 2 (a). A dBQ penalty of 1dB is often used as a network engineering measure for the above filter concatenation effect [10], although this value can vary depending on the application. Depending on the network performance margin and the number of cascaded optical filters the above selected penalty value can vary producing different specification requirements on the individual filter transfer functions (ie. ripple, 3dB-bandwidth) and laser/filter maximum allowed frequency misalignment. The use of different WADM technologies should be considered for reducing the impact of the filtering effect. Using interferometer-based grating designs [12] at each one of the WADMs of Fig. 1 reduces the number of filtering functions that a signal experiences since only the add/drop channels are filtered. The recently introduced reconfigurable PurePath™ Wavelength Modular Switch which is a reconfigurable add/drop switch with integrated filtering capabilities based on thin-film technology [13] will provide the same benefits as the interferometer-based grating designs. In addition it provides the ability to drop/add dynamically from a set of wavelengths supporting future network reconfigurability.

(e) Optical Crosstalk

Optical crosstalk and in particular common channel can be very detrimental since it is difficult to be eliminated by filtering and beats with the signal at the receiver introducing interferometric noise [14]. Common channel refers to crosstalk arising from different lasers all at the same nominal wavelength or it can originate from the same laser, in which case it is called multipath. In the network case study of Fig. 1, common channel crosstalk terms are generated at both WADMs as well as XCs. Using the parallel WADM configuration of Fig. 2 (a) will introduce a large number of multipath crosstalk terms. In particular the ones originating due to the two adjacent channels (provided that these channels will follow the worst-case path of Fig.1) will accumulate at each WADM. The use of the reconfigurable PurePath™ Wavelength Modular Switch introduced above will result in no generation of any multipath crosstalk terms for all the pass-through channels. Other common channel crosstalk terms due to the return path (not shown in Fig. 1) will be present if either the above reconfigurable design is used or any interferometer-based grating design. The level of crosstalk can then be reduced by using separate devices for the add and the drop functions.

Common channel crosstalk terms will also be generated at XCs 3 and 11 due to the MUX/DMUX pairs and the switching fabrics of the design of Fig. 2 (b). Although the channel following the worst-case path of Fig. 1 does not traverse XC 11, common channel crosstalk generated at XC 11 can enter its path through the return signal. All possible crosstalk terms can be collected and the error probability for the channel that follows the worst-case path of Fig. 1 in the presence of crosstalk can be evaluated based on a closed-form expression presented in [15], [16]. The power penalty at the desired BER due to crosstalk can be evaluated for different individual crosstalk levels of the network devices. Depending on the network margin available different crosstalk levels can be tolerated.

V. Conclusions

In summary, we have presented a study of the transport layer of a transparent metro DWDM network describing all the major effects that need to be taken into consideration when engineering such a network. The impact of each effect, mitigation techniques and trade-offs have been discussed with emphasis on currently available optical components and leading technologies. In particular, we have shown that the use of power equalizers can determine the feasibility of a network from a performance viewpoint. The use of the Wavelength Selective Switch ™ which is based on liquid-crystal technology can be a very cost effective solution since it can provide the necessary dynamic power equalization and at the same time the switching capability for all the channels. The use of low negative dispersion fiber such as MetroCor ™ fiber can extend the reach of optical paths for distances beyond 200 km by dealing with the problem of dispersion/chirp very effectively making metro applications more feasible and cost effective. Finally the reconfigurable PurePath™ Wavelength Modular Switch addresses the important problem of filter concatenation and optical crosstalk by providing a reconfigurable add/drop switch with integrated filtering capability.

IV. Acknowledgments

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References

[1] C. A. Brackett *et. al.*, "A scalable multiwavelength multihop optical network: A proposal for research on all-optical networks", *J. Lightwave Technol.*, 11(5-6): 736-753, May/June, 1993.

[2] R. E. Wagner *et. al.*, "MONET: Multiwavelength Optical Networking", *J. Lightwave Technol.*, (14(6): 1349-1355, June 1996.

[3] S. B. Alexander *et. al*, "A precompetitive consortium on wide-band all-optical networks", *J. Lightwave Technol.* 11(5-6): 714-735, May/June, 1993.

[4] A. A. M. Saleh and J. M. Simmons, J. Lightwave Technol. 17(12): 2431-2448, Dec. 1999.

[5] A. R. Ranalli, B. A. Scott, J. P. Kondis, "Liquid Crystal-Based Wavelength Selectable Cross-connect", *ECOC European Conf. On Opt. Commun.*, pages 2.143-2.146, Nice, France,Sep. 1999

[6] C.-C. Wang, I. Roudas, I. Tomkos, M. Sharma, and R. S. Vodhanel, "Negative Dispersion Fibers for Uncompensated Metropolitan Networks", *ECOC European Conf. On Opt. Commun.*, Munich, Germany, to appear Sept. 2000.

[7] G. P. Agrawal, *Fiber Optic Communication Systems*. New York: John Wiley & Sons, 1992.

[8] N. Antoniades et. al, "Computer Simulation of a Metro Ring Network", *LEOS Summer Topical Meetings*, paper ThC1. 0004, Miami, FL., July 2000.
[9] D. A. Atlas, A. F. Elrefaie, M. B. Romeiser, and D. G. Daut, Optics Letters, vol. 13, p. 1035, 1988.
[10] N. N. Khrais, A. F. Elrefaie, R. E. Wagner, and S. Ahmed, "Performance Degradation of Multiwavelength Optical Networks Due to Laser and (De)Multiplexer Misalignments", *IEEE Photon. Technol. Letters*, vol. 7, no. 11, Nov. 1995, pp. 1348-1350.
[11] I. Roudas, N. Antoniades, R. E. Wagner, S. F. Habiby and T. E. Stern, "Influcence of filtered ASE noise and optical filter characteristics on the performance of multiwavelength optical networks", *ECOC European Conf. On Opt. Commun.*, Edinburgh, Scotland, Sept., 1997, pp. 2.143-2.146.
[12] F. Bilodeau et. al., "High-performance wavelength-division multiplexing/demultiplexing using an all-fiber Mach-Zender interferometer and photoinduced Bragg grating", *in Proc. OFC'95*, San Diego, CA, Feb. 26-Mar.3, 1995, pp.130-132.
[13] M. A. Scobey and D. E. Spock, "Passive DWDM components using microplasma optical interference filters", *in Proc. OFC'96*, San Jose, CA, Feb. 25-Mar.1, 1996, pp.242-243.
[14] E. L. Goldstein, L. Eskildsen, and A. F. Elrefaie, "Performance implications of component crosstalk in transparent lightwave networks", *IEEE Photon. Technol. Letters*, vol. 6, no. 5, May 1994, pp. 657-660.
[15] K- P. Ho, *IEEE/OSA J. Lightwave Technol.*, vol. 17, n.2, pp.149-154, February 1999.
[16] X. Jiang, I. Roudas and K. Jepsen, "Asymmetric Probability Density Function of a Signal with Interferometric Crosstalk in Optically Amplified Systems", *in Proc. OFC'00*, Baltimore, MD, March 2000, paper ThJ4.