# GRATINGS, AMPLIFIERS AND SOURCES FOR HIGH SPECTRAL EFFICIENCY SYSTEMS

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The evolution of the fiber-optic communications market towards finer granularity, better flexibility and lower costs continue to drive systems toward increased capacity (Gbps/fiber) at lower $/bps/km cost. New engineering challenges emerge as bit rates are increased and channel spacing is reduced. Examples of these difficulties are seen when low bit-error-rate accuracies are maintained while channel spacing is reduced, and when effective thermal management is maintained as bit rate increases and module sizes shrink. Consequently, new transmission components must facilitate higher spectral efficiency, higher flexibility and lower cost.

The drive to increase capacity by increasing spectral efficiency is evident in several recent developments. Examples of such are 10Gbps at 100GHz channel spacing, 10Gbps at 50GHz, and 40Gbps at 100GHz, which correspond to 0.1, 0.2 and 0.4bps/Hz, respectively.

The components most affected by the increase in spectral efficiency requirement are filters, transmitter lasers and amplifiers. Filters must have ever increased bandwidth utilization, with ever narrower channel spacing; while lasers must have higher power and better wavelength stability. Amplifiers, in turn, carry an ever-increasing load of optical channels.

One of the factors influencing signal bandwidth is transmission format. There is a consensus that at 10Gbps and below, NRZ transmission format is preferred, while, at 40Gbps, RZ has a slight advantage in transmission penalties over NRZ. Although the majority of 40Gbps development is carried out using RZ format, which roughly doubles the bandwidth of the signal as compared to NRZ, it is still desirable to relax the requirements on inline components by optimizing the signal bandwidth with a single-sideband RZ variation.

## Fiber Bragg Gratings (FBGs)

Filters fall into two general categories: mass multiplexing/demultiplexing and selective Optical Add/Drop Multiplexers (OADMs). Mass multiplexing and demultiplexing usually occurs at the origination and receive sites while OADM occurs at intermediate sites where typically up to 20% of channels are dropped.

Fiber Bragg gratings (FBGs) are emerging as the component of choice for optical add/drops. This is attributed to the near ideal characteristics that apodized FBGs have exhibited for high channel isolation, high channel bandwidth utilization and group delay. A quick comparison of key features for three filter technologies is highlighted in Table 1. Note that this table is on a per channel basis and does not include cumulative effects such as multipath interference and in-band scattering that become significant with multi-channel OADMs. Other parameters, such as in-band group delay, limited sideband isolation, and waveguide phase errors, typical of multi-cavity interference filters and array waveguides, significantly reduce the usable bandwidth, particularly at 10Gbps and higher.

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| | Fiber Bragg Gratings | Array Waveguides | Interference Filters |
|---|---|---|---|
| Channel Spacing | 12.5, 25, 50, 100, 200GHz | 50, 100, 200GHz | 50, 100, 200GHz |
| Adjacent Channel Isolation | High, >30dB at 2.5GHz spacing | Medium, >24dB at 100GHz | Medium, >20-25dB at 100GHz |
| Express Insertion Loss | Low, <1dB/ch, Low after multiple dropped channels | High, <5 to 7dB | Low, <1dB/ch, High after multiple dropped channels |
| Power Consumption | Passive | Active | Passive |
| Add/Drop Insertion Loss | Low, <1dB per channel | High, <5 to 7dB | Low, <2dB per channel |
| Channel Count Scalability | Low to Medium | High | Medium |
| Channel Flexibility | High | Low | High |
| Bandwidth Efficiency Potential (bps/Hz) | ~0.8 | ~0.5 | ~0.2 |

Table 1. Comparison of key features between three common filter technologies. Array waveguides (AWGs) are common in mass muxing and dumultiplexing due to their cost advantage, while fiber Bragg gratings (FBGs) have the advantage of performance and flexibility at ≤50GHz channel spacing.

Channel flatness, and channel-to-channel uniformity also contribute to bandwidth reduction as the DWDM signal passes through multiple cascades, which in-turn limits the maximum number of cascaded OADMs before regeneration becomes necessary. Since the number of cascaded OADMs is defined by the number of amplifier spans in systems, which is 6 to 7 in long-haul and up to 20 for ultra long-haul systems, it becomes imperative that bandwidth utilization for filters is as wide as possible.

Figure 1 shows the reflectivity and group delay for an FBG that exhibits a bandwidth utilization factor of 75% and constant reflectivity of >99.9% (>30dB transmission loss) over the full drop window. These filters are tested at 10Gbps and show that a $<10^{-11}$ bit-error-rate (BER) is obtained for constant received power throughout the useful band. The filter shown in Fig. 1 is designed, using an inverse scattering algorithm, to have a 30dB reflective bandwidth of 50GHz and 0.5dB reflective bandwidth of 37.5GHz. The grating is 12cm long and has a series of phase-shifts along its length, as shown in Fig. 2.

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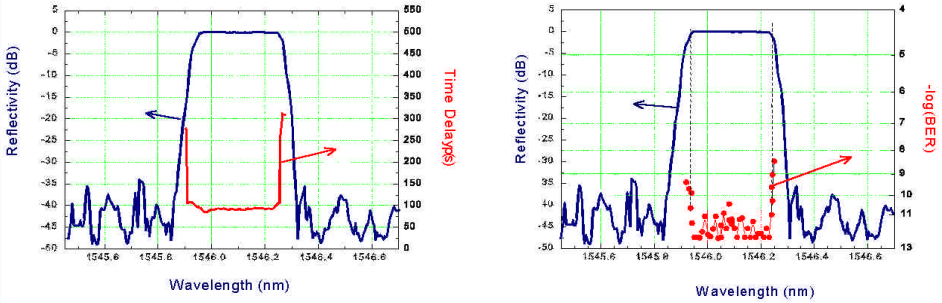



Figure 1. Reflectivity, time-delay and BER spectra of a 50GHz FBG. Measurement is carried out at 10Gbps showing BER < $10^{-11}$ with channel utilization of 75%.

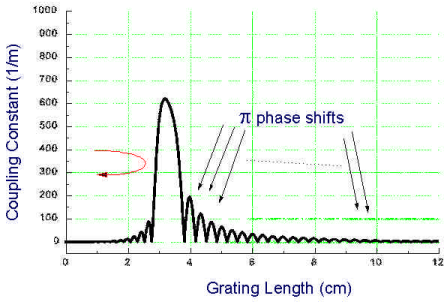



Figure 2. The refractive index profile of the strongly apodized 12cm FBG of Fig. 1.

These filters are written using a continuous grating writing technique that has full control of where the individual grating planes are written along the length of the grating. By de-phasing subsequent grating-planes with respect to each other, full control of the amplitude and phase profiles in the grating is obtained. The combination of the phase-shifts and the periodic envelope function of the refractive index ensure not only the square spectral response of the grating, but also the linear-phase (also referred to as constant group delay or nearly dispersion-free) performance. By design, these gratings are single ended and are not used bi-directionally.

## Cladding Pumped Amplifiers

Erbium-doped fiber amplifiers (EDFAs) have essentially not changed in concept since their initial commercial deployment. This is due mainly to the low erbium concentrations in the core of the doped fiber, limited by the saturation of the erbium ions. Another limitation is the three-level erbium ion itself, which requires high concentrations of pump power in the core to maintain population inversion, hence the requirement for small core diameter and core-pumping. The maximum amplifier output is then limited by the total pump power that can be delivered to the erbium-doped fiber via a single mode fiber.

Ytterbium (Yb) co-doping has radically changed these rules with its wide absorption spectrum and by the efficient transfer of pump power to the erbium. This has opened the door for higher erbium concentrations, the change in pumping configuration from core-pumping to

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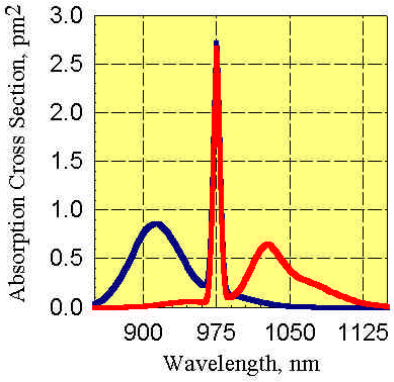



Figure 3. Absorption and emission spectra of Er/Yb co-doped fiber, showing a narrow absorption peak about 976nm and a broad absorption peak at 915nm.

clad pumping, as well as the use of multimode pumps. These pumps can be coupled to the cladding using multimode fibers, and several can be coupled to the same fiber to achieve higher amplifier powers. The benefit of cladding pumping becomes evident with the $/dBm cost reduction for amplifiers as the potential of lower cost multimode pumps is realized.

The broad absorption band of co-doped Er/Yb introduces another major benefit. As shown in Fig. 3, the broad 915nm absorption band conveniently removes the requirement that pump wavelength be confined to the common ±2nm absorption region of the erbium, about 980nm. At 915nm, the absorption spectrum is more than 15nm wide; hence pump wavelength drift with temperature has no significant impact on the pump absorption, which is the case with EDFAs. This removes the need to keep the pump at a constant temperature with a thermo-electric cooler (TEC), or to add an external stabilizing grating.

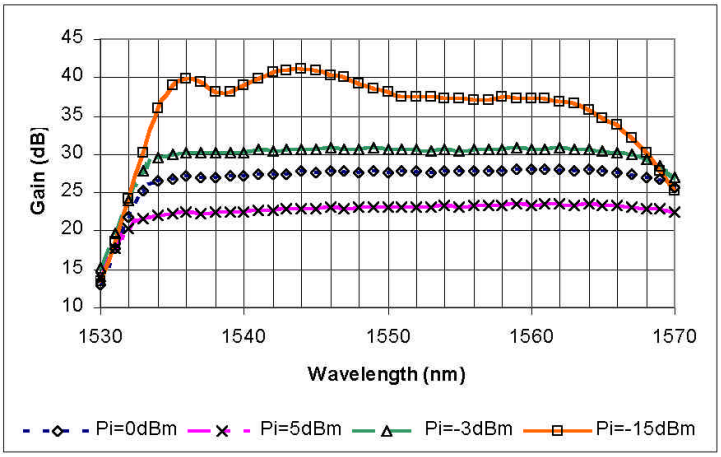



Figure 4. Typical output spectra for Er/Yb co-doped high power amplifier for input power levels of –15dBm, -3dBm, 0 dBm and 5dBm.

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## Impact of Optical Power on Fiber Nonlinearities

It is generally desirable to launch into the fiber with as much power per channel as possible to gain incremental transmission distance. However, nonlinear effects in the fiber limit the amount of power transmitted per channel. Therefore, span distances between amplifiers are usually limited by the nonlinear effects at the transmitter side and by OSNR degradation or receiver sensitivities at the receive side.

The dominant factors for transmission impairments of DWDM externally modulated systems are Cross-Phase Modulation (CPM) and Self-Phase Modulation (SPM). These generally limit the power per channel to <3dBm for 10Gbps, and <0dBm for 40Gbps systems. There are other variations, for example quasi-soliton systems may tolerate incrementally higher power levels per channel.

A power limit of 3dBm per channel at 25GHz, or 160 channels in the C-band, requires a 22dBm amplifier. Such power levels, considered high for core-pumped EDFAs, are easily surpassed with cladding pumped amplifiers. For example, a 31dBm amplifier has enough power to distribute to eight sub-amplifiers each at 22dBm. Not only is the high channel count per fiber driving the need for higher amplifier powers, but additional incurred losses, such as spectral flattening filters in amplifiers or dispersion compensation fibers may demand even higher power levels from cladding pumped amplifiers.

Other nonlinear effects have thresholds that occur at higher power levels per channel than CPM and SPM. For example, Stimulated Brillion Scattering (SBS) occurs at about 8dBm/ch, while Stimulated Raman Scattering (SRS) occur at much higher levels. Direct modulated transmissions have higher thresholds due to the averaging effect of chirp. Alternately, externally modulated systems can deploy prechirping to minimize SBS, although this does not reduce the dominating contributions of CPM.

## Distributed Feedback (DFB) Fiber Lasers

Transmission systems place three main requirements on lasers: high optical power, low heat generation, and low spectral drift. High optical power minimizes the need for amplification prior to transmission, while low heat generation minimizes the thermal impact on the modulator/transmitter. However, the most critical requirement for high spectral efficiency systems is low spectral drift of the source. Drift of the transmitter laser directly impacts transmission impairments due to the compounded change in insertion loss and dispersion in a cascaded laser/mux/demux combination, particularly as the laser detunes away from the ITU defined frequency.

Many spectrally efficient systems have the signal bandwidth occupy 40% or more of channel spacing, such as 10Gbps in 25GHz spacing or 40Gbps in 100GHz spacing. The remaining bandwidth is reserved as system tolerance that covers many factors, such as laser thermal and aging drift, mux/demux wavelength drift, or bandwidth allocated for channel isolation to reach >25dB.

DFB lasers have about 0.1nm/°C in thermal drift, or 12GHz/°C. To use these lasers in 50GHz or lower channel spacing, it is required to maintain stability to 0.2°C or better at operating case temperatures that span from 0 to 65°C. Such conditions are not practical. Hence, many sys-

tems employ wavelength lockers to maintain stability within ±2GHz, while simultaneously deploying filters with channel utilization factors of >50%.

An alternative to the DFB laser/locker combination are DFB fiber lasers. These devices are in-fiber gratings written in Er/Yb co-doped fiber and core-pumped with 976nm pump lasers. The fiber lasers are designed to have >40dB polarization extinctions and are athermally packaged (Fig. 5). The advantage of such technology lies in the potential for small footprint,

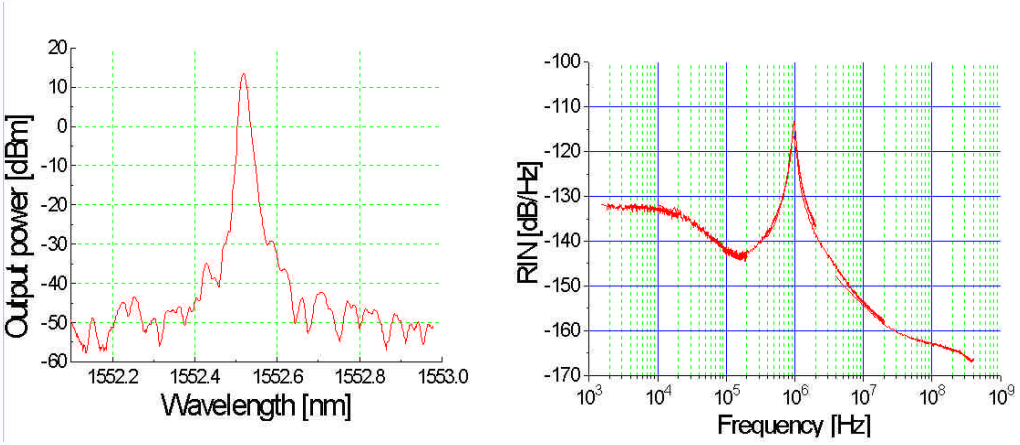



Figure 5. Output power and RIN characteristics for a DFB fiber laser. Note the high sidemode suppression and power (left) and low RIN at operating data rates >$10^8$ (right).

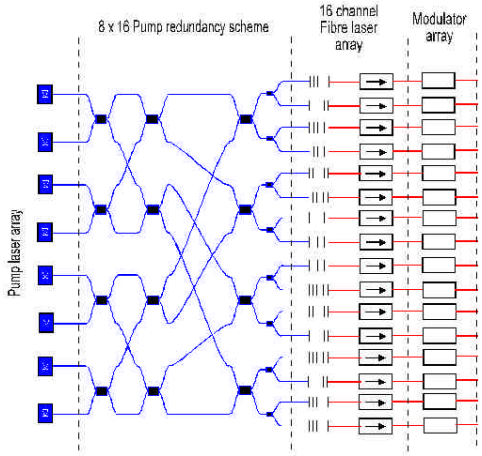



Figure 6. Example configuration for the DFB fiber laser array. The pump redundancy fabric protects against failure of individual pumps by an increase of the power of the surviving pumps. An isolator is used between the fiber laser and the external modulator.

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ease of manufacture, and low inherent thermal sensitivity. Note that the thermal drift coefficient of glass is an order of magnitude less than semiconductor materials.

In addition, the in-fiber approach makes it possible to cascade these DFB fiber lasers in a fiber array, and pump the array with a set of pump lasers that are positioned elsewhere in the system (Fig. 6). This isolates the heat generating pumps from the lasers, commonly placed in the vicinity of the transmitter opto-electronics.

## Conclusion

Novel solutions that meet the market needs for high bandwidth efficiency, lower cost and lower power consumption components are presented. Those solutions are based on fiber Bragg grating filters, Er/Yb co-doped amplifiers and DFB fiber lasers.

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