Adaptive Gain Equalizer in High-Index-Contrast SiON Technology

B. J. Offrein, F. Horst, G. L. Bona, R. Germann, H. W. M. Salemink, and R. Beyeler

***Abstract*—An adaptive gain equalization filter is presented. The filter is based on the resonant coupler principle, a cascade of power couplers and delay lines. Reconfigurability and tuning is achieved by varying coupling strength and delay line length via the thermo optic effect. A device consisting of seven delay line stages was realized in high-index-contrast silicon–oxynitride technology. This device flattens the ASE spectrum of an EDFA to a ripple of less than 0.5 dB over 35 nm. The on-chip losses are 2 dB.**

***Index Terms*—Adaptive, erbium amplifier, gain equalization, reconfigurable, silicon–oxynitride (SiON), waveguide, wavelength-division multiplexing (WDM).**

I. Introduction

In a wavelength-division-multiplexing (WDM) optical network, it is important to maintain equal signal power levels over the WDM spectrum. Power nonuniformities occur due to the nonflat spectral responses of components in the network. For example the nonflat gain spectrum of an erbium-doped fiber amplifier (EDFA) leads to a power imbalance of the WDM channels, especially if many EDFA's are cascaded [1]. To restore the power balance of the WDM channels one can correct every channel individually using a channel equalizer [2] or a de-mux/mux combination with variable optical attenuators. This is an appropriate solution if the power variation from channel to channel is not correlated. However, if the channel power nonuniformity is caused mainly by the EDFA spectral gain, a correlation exists and a gain equalizer will generally be a simpler solution. An adaptive equalizer is of great interest because the gain spectrum of the EDFA depends on its signal-input power. Hence, changes in the network load require a change of the equalization response. The adaptive gain equalizer presented here is relatively simple and small compared to previously reported devices [3]. Therefore, and because of the applied waveguide technology, it is potentially inexpensive to produce.

II. Adaptive Equalizer Concept

The adaptive equalizer is a cascade of variable couplers and delay lines, also called a resonant coupler (RC) or cascaded Mach–Zehnder interferometer (MZI) [4]–[6]. A schematic drawing of a two-stage RC device is shown in Fig. 1. In this device the delay lines, which are all of equal length, set the free spectral range (FSR) of the response. A one-stage device is a simple asymmetrical MZI and its response can be described with one harmonic. With more stages, the spectral response is a Fourier-series-type function with the highest harmonic having a periodicity of FSR/N, where N equals the number of stages. The ability to flatten an arbitrary gain spectrum increases with the number of stages and requires full tunability of all the coupling and delay line sections. As depicted in Fig. 1, each variable coupler is a simple symmetric MZI that can be adjusted using a phase control on one of the arms.

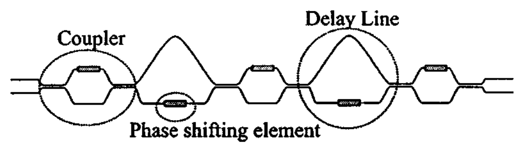

Fig. 1. A two-stage RC component consisting of three tunable couplers and two tunable delay lines.

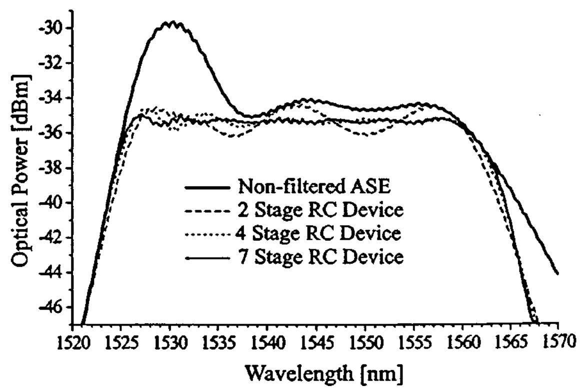

Fig. 2. Simulation of the flattening of the EDFA ASE spectrum by two-, four-, or seven-stage RC filter.

III. Gain Flattening Simulation

In this letter, we show the equalization abilities of the RC device by flattening the amplified spontaneous emission (ASE) spectrum of our EDFA. In Fig. 2, the ASE spectrum is represented by the bold solid line; the dashed lines indicate the optimally achievable flattening simulated for devices with two, four, and seven stages. The optical parameters of the device, the power splitting ratios in the couplers, and the phase settings of the delay lines are found using a Levenberg–Marquardt optimization algorithm [7]. The FSR was chosen to be 40 nm, slightly larger than the -6-dB bandwidth (35 nm) of the ASE spectrum of the EDFA.

A seven-stage RC device should be able to flatten the ASE spectrum to a ripple of less than 0.5 dB over a spectral width of 35 nm as presented by the thin solid line in Fig. 2. In the following, our experimental results on such a gain equalizer are

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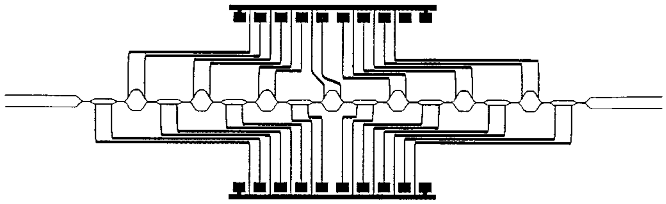

Fig. 3. Device layout (not to scale) showing waveguids, chromium heaters and aluminum leads. Actual size of the device including leads is 75×6 mm^2.

presented.

IV. Device Realization

The cascade of variable couplers and delay lines, shown in Fig. 1, contains many bend sections. Hence, a small radius of curvature is of high interest to keep such RC-type devices compact. In standard fiber-matched waveguiding structures the minimum bending radius is limited to about 15 mm. Our silicon-oxynitride (SiON)-based structure has a higher refractive index contrast of 3.3% and a smaller waveguide size of 2×3 μm^2 [8]. This stronger guiding of the mode allows a minimum bending radius of only 1.5 mm and thus enables the cascading of many delay line stages in a compact way.

The waveguide propagation losses at 1550 nm are as low as 0.1 dB/cm. The waveguide field profile is not matched to that of a standard single-mode fiber, but fiber-to-chip losses of <0.7 dB per facet can be obtained using a short stretch of small-core fiber fusion-spliced to the standard fiber and butt-coupled to the chip.

We have reported previously on polarization-independent resonant coupler and switching devices realized using this waveguide technology [9], [10].

We realized a seven-stage device with an FSR of 40 nm, which conforms to the simulation data shown in Fig. 2 by the thin solid line. The layout of this device is shown in Fig. 3. Its size, including heater leads and bonding pads, is 75×6 mm^2. The device consists of seven delay line stages and eight variable couplers, each with an independently controllable phase shifter, formed by a chromium heater. The phase shifter response time is less than 1 ms and the sensitivity is 2π rad./440 mW/heater.

V. Measurements

The reconfigurability of the seven-stage gain equalizer is shown by two different measurements. First the device is used to flatten the EDFA ASE spectrum as shown theoretically in Fig. 2. In the second example an input signal at 1563 nm is amplified by the EDFA. This leads to a change of the ASE spectrum. This changed ASE spectrum is again flattened with the same device using different parameter settings.

In order to find the optimum parameter settings, i.e. the voltages for the heaters, the device is embedded in an optimization loop. A personal computer controls the individual voltages over the heaters and reads the spectral response of the device from an optical spectrum analyzer. An iterative optimization procedure based on a Levenberg–Marquardt algorithm [7] compares

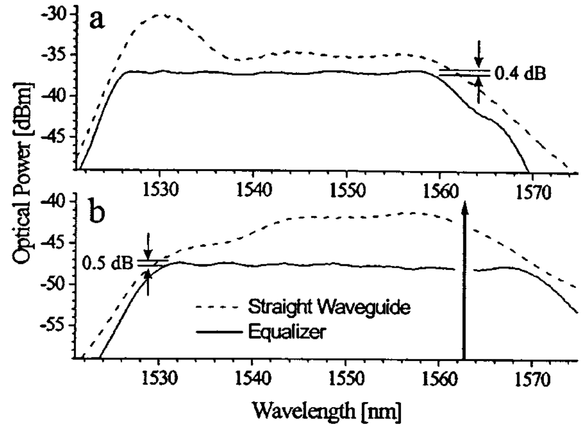

Fig. 4. Measurement of the flattened EDFA ASE spectrum (a) without and (b) with a 1563-nm signal amplified by the EDFA.

the measured and desired responses and optimizes the heater settings accordingly. This procedure requires typically 30 to 40 iterations to find the desired response.

The dashed line in the top graph of Fig. 4 shows the ASE spectrum of our EDFA after propagation through a 75-mm-long straight waveguide. The solid line represents the experimentally obtained flattened ASE spectrum that shows a ripple of less than 0.4 dB over a range of 35 nm centered around 1543 nm.

Then, an input signal at 1563 nm was inserted in the EDFA, which drastically changed the ASE spectrum. The equalizer was reoptimized using the same procedure and again a ripple of less than 0.5 dB was obtained over 37 nm, centered around 1550 nm as presented in Fig. 4(b).

Note that Fig. 4 compares the transmitted power of a straight waveguide with that of the equalizer, so Fig. 4 shows the excess loss of both the optimization process and the device itself. The excess loss is about 1 dB, and the total on-chip loss of the device is about 2 dB.

The batch containing this device showed a small polarization dependence, so the measurements presented here are all performed for TE polarized light only.

VI. Application Aspects

The device presented here consists of seven stages. The simulations illustrated in Fig. 2 show that good results can already be obtained with a four-stage device. Furthermore the characteristic ASE peak around 1530 nm disappears if an input signal is injected into the EDFA as in Fig. 4(b). Hence, devices of this type with only three, four,or five stages can already be of significant practical interest in order to dynamically flatten the gain of EDFA's in WDM networks.

For the measurements described in the previous paragraphs, we used an iterative optimization procedure, which measures the direct effect of the heater voltage on the total device response. In this case, the relation between voltage and phase shift for the individual heaters does not need to be known, but the optimization needs several iterations.

In a network application, this procedure cannot be followed. In this case, the relation between voltage and phase-shift must be measured for each heater individually and stored in a look-up table. When a reconfiguration of the equalizer is needed, the

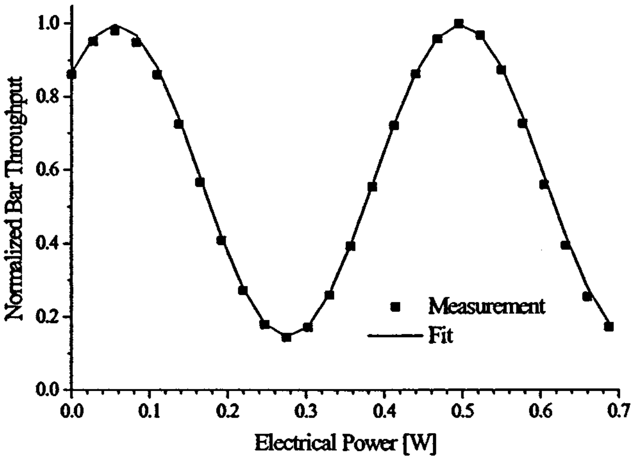

Fig. 5. Tuning characteristic of a variable coupler.

phase settings for all elements can be computed from the required equalization curve using standard design techniques for finite impulse response filters [5]. The corresponding heater voltages are then found using the data in the look-up table and set for all heaters simultaneously. In this way the complete reconfiguration of the device can take place within 1 ms.

The characterization of all individual heaters proceeds in three steps. First, all tunable couplers are tuned to zero cross-coupling by optimizing the entire device for minimum output power at its cross output using the iterative procedure described in the previous section. Second, the tunable couplers can be characterized by tuning each one individually throughout its complete voltage range while leaving the others in the zero cross-coupling state and recording the output power at the cross and bar outputs of the device. An example of the resulting tuning curve for one coupler is shown in Fig. 5. Third, for each tunable delay line we can build an asymmetric MZI by setting its adjacent tunable couplers to 50% power coupling using the previously obtained tuning curves. We can now obtain the tuning curve for the delay line by tuning the heater throughout its complete voltage range and measuring the cross and bar output powers at a fixed wavelength.

When in this way the tuning curves for all heaters are determined, we can replace the slow iterative optimization procedure by a direct, fast calculation of the required heater settings to obtain a given filter curve.

VII. CONCLUSION

An adaptive gain equalizer was presented based on a cascade of variable couplers and delay lines. The device is realized in high-index-contrast SiON technology. Reconfigurability is obtained using the thermooptic effect. The ASE spectrum of an EDFA was flattened to peak-to-peak variations of less than 0.5 dB over 35 nm. Fiber-to-fiber losses of about 3.5 dB can be achieved.

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