Experimental demonstration of a non-linear optical fibre combiner

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Optical splitters give an unwanted 3-dB loss when used as combiners. This is avoided with optical switches, but these need control functions to synchronize with the optical signals. A recently proposed device [1] provides the combiner function without control signals, by using a nonlinear Mach-Zehnder interferometer. In the experiment reported here this combiner was realized with fiber components, with SOAs acting as the non-linear phase shifting elements. With this device the self-routing combiner is demonstrated for the first time: optical signals on either of the two input ports are guided to one output port, without any control mechanism in the interferometer. The non-linear effect used is self phase modulation, caused by carrier depletion in the SOAs as they approach saturation. The optical power at which the non-linear switching occurred was about –3 dBm.

Introduction

An essential function in optical fiber networks is the combining of optical signals. This is e.g. required in an optical fiber tree, as is used in PON systems. Usually the combiner is a passive function, obtained with fused fiber couplers or planar Y-junctions. The disadvantage of these for combining signals is an inherent 3-dB loss. This is avoided with optical switches, but then control functions are needed to synchronize the switch with the signals.

Recently [1] it has been proposed to solve this dilemma with a non-linear optical device, in which the signals themselves set the optical path. Previously proposed non-linear switches use either control pulses [2], or are non-interferometric ([3]), and therefore require large non-linear (NL) effects. The combiner in [1] is a Mach-Zehnder interferometer, in which unequal optical powers in the two branches give non-linear phase shifts. The penalty here is incomplete interference, but this is small: e.g. a power ratio of 75/25 results in 0.3-dB loss.

The non-linear combiner in [1] was aimed at an integrated realization. It is also possible to realize it with fiber based, off-the-shelf, components. This paper describes this realization, with Semiconductor Optical Amplifiers (SOAs) used as non-linear elements. In this way a proof of principle of the low-loss combiner is given.

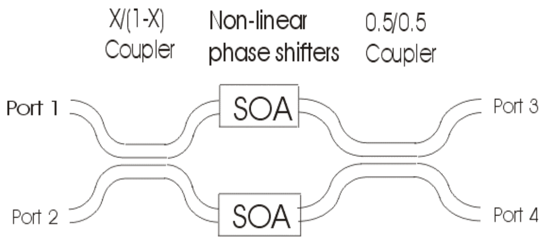

***Fig.1**: Layout of the fiber based non-linear combiner. The SOAs provide for the non-linear phase shift $\Delta\Phi_{NL}$. The linear phase shift $\Delta\Phi_{L}$ results from length differences.*

Device concept

The interferometer contains two couplers and two non-linear phase shifters (fig.1). The output coupler is a 50/50 coupler, the input coupler however is unbalanced, with a coupling ratio of x/(1-x). This leads to an unequal power distribution in the two branches of the interferometer, and therefore to a non-linear phase shift difference $\Delta\Phi_{NL}$. Also a linear phase shift difference $\Delta\Phi_L$ is required. The output powers depend on these two phase shifts. The linear phase shift difference $\Delta\Phi_L$ is independent of which input port is used. However, the non-linear phase shift difference $\Delta\Phi_{NL}$ changes sign when changing the input port, because the highest optical power is then present in the opposite branch. The following output powers are found for the four different paths through the circuit, if unit input power is assumed:

$$P_{1\to3} = 0.5 - \sqrt{x(1-x)}\cos(\Delta\Phi_{NL} + \Delta\Phi_L) \qquad \text{(eq. 1a)}$$

$$P_{1\to4} = 0.5 + \sqrt{x(1-x)}\cos(\Delta\Phi_{NL} + \Delta\Phi_L) \qquad \text{(eq. 1b)}$$

$$P_{2\to3} = 0.5 + \sqrt{x(1-x)}\cos(-\Delta\Phi_{NL} + \Delta\Phi_L) \qquad \text{(eq. 1c)}$$

$$P_{2\to4} = 0.5 - \sqrt{x(1-x)}\cos(-\Delta\Phi_{NL} + \Delta\Phi_L) \qquad \text{(eq. 1d),}$$

The combiner is obtained if both $\Delta\Phi_{NL}$ and $\Delta\Phi_L$ are $\pi/2$. In that case equations (1) reduce to:

$$P_{1\to3} = P_{2\to3} = 0.5 + \sqrt{x(1-x)} \qquad \text{(eq. 2a)}$$

$$P_{1\to4} = P_{2\to4} = 0.5 - \sqrt{x(1-x)} \qquad \text{(eq. 2b)}$$

This means that the output powers are no longer dependent on which input port is used. Signals from both input ports are for the largest part transferred to output port 3. The value of "x" is a compromise between the acceptable loss due to incomplete interference, and the non-linear phase shift difference, which requires a large difference in power in the two branches.

SOA-characterization

The combiner requires a non-linear phase shift of $\pi/2$, induced by the incoming optical signal. It is known [4] that optically induced phase shifts can be obtained in SOAs, caused by carrier depletion. The reduction of the free carrier concentration in the SOA at high enough input powers gives an increase in the refractive index, and thus a phase shift.

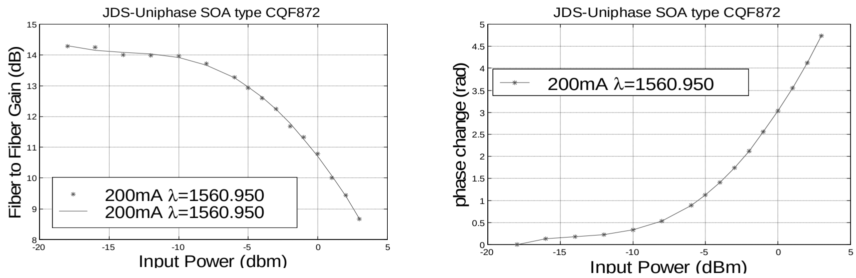

***Fig. 2**: Left: Gain saturation measured for the SOAs used in the combiner. Right: Phase change versus input power, as derived from the gain saturation.*

The SOAs used are JDS-Uniphase SOA-type CQF872. Their gain saturation is shown in fig. 2 (left). From this the phase change in the SOA is derived for the measured linewidth enhancement factor α of 7.2 (see fig. 2, right). For a power difference of 9.5 dB at the input of the two SOAs, as is used in the experiment, $\Delta\Phi NL=\pi/2$ is expected for –1.5 dBm.input power.

Since the SOAs are used in the saturation regime, the power ratio at the entrance of the output coupler of the MZI is different than that from the input coupler. In fact it will be closer to one, because the highest power in the branches experiences the lowest gain. This is beneficial, it implies that a larger fraction of the power is present at the preferred output port.

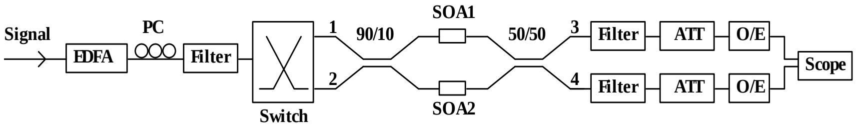

***Fig.3**: The experimental setup. EDFA: Erbium Doped Fibre Amplifier, PC: Polarization controler, ATT: Attenuator,O/E: Opto-Electronic converter.*

Experimental procedure

In the experimental set-up (fig. 3) the major problem is the stability. Due to environmental influences the value of $\Delta\Phi_L$ drifts during the experiment, influencing the output power distribution. Therefore a measurement procedure is devised that enables separate determination of $\Delta\Phi_{NL}$. This is achieved as follows. An optical switch alternates the signal between the input ports, with a frequency (100 Hz) high enough to neglect environmental drift in one switching period. The difference in the powers from the output ports then shows a periodic pattern, since the output power distribution depends on the input port used. This pattern slowly changes in amplitude and average level, due to the environmental drift of $\Delta\Phi_L$. For $\Delta\Phi_L=0$ and $\Delta\Phi_L=\pi$ the maximum amplitude A of this pattern is obtained. This maximum is according eqs. 1:

$$A_{\max} = 4\sqrt{x(1-x)}\left[\cos(\Delta\Phi_{NL})\right] \qquad \text{(eq. 3)}$$

By observing over time the output power distribution A_{max} is determined. For operation as a combiner, $\Delta\Phi_{NL}=\pi/2$, it becomes zero. The switching of the signal between the input ports has then no influence. The drift in $\Delta\Phi_L$ only shows up in a slow variation of the output power distribution. With $\Delta\Phi_L=\pi/2$ for input in both input ports the light is guided primarily to port 3.

The experimental setup contains an inline EDFA-amplifier, in order to have a large range of powers available at the combiner. Optical bandpass filters are used to eliminate the ASE. Attenuators keep the detected powers in the same range, to avoid saturation in the detection. Detection is done with homemade opto-electronic converters. The unbalanced coupler in the MZ-interferomenter is a 90/10 coupler (so x=0.1). Experiments are done at a wavelength of 1560.95 nm. The SOAs are electrically powered with 200 mA current.

Results

Two sets of measurements are done to determine the operation of the self-routing combiner.

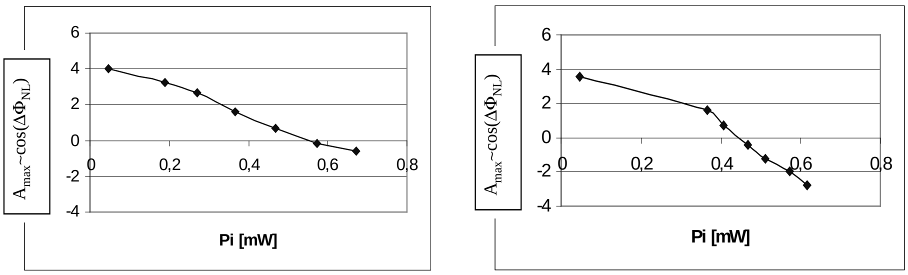

***Fig. 4**: Two measured series. Maximum output power difference for injection in the two input ports 1 and 2. For a zero value both signals from port 1 and from port 2 are guided to the same output port.*

These measurements are performed a few hours after each other. Fig. 4 shows the A_{max} as a function of the input power into the Mach-Zehnder interferometer. In the first series (left) A_{max} vanishes at 0.55 mW (-2.6 dBm), in the second series (right) at 0.47 mW (-3.3 dBm). At these values the optimal combiner function is found. The difference can be attributed to a change in polarization, because the SOAs show moderate polarization dependence. (Polarization state is relatively stable, as compared with the drift of the phase shift $\Delta\Phi_L$, but changes over longer periods of time). Fig. 4 verifies that indeed an optically induced phase shift is occurring, and that this phase shift results in a combiner: both input signals (from port 1 and 2) are guided to the same output port. The gain saturation causes the measured curves in fig. 4 to deviate from the cosine shape that is expected from eqs. (3): as the input power increases not only a non-linear phase shift $\Delta\Phi_{NL}$ appears, but also the power ratio between the two branches changes.

Because of the environmental drift the combiner operation can only be directly observed if $\Delta\Phi_{NL}$ is close to $\pi/2$. It can however be derived from the measured A_{max} in fig. 4, if the power ratio over the two MZI-branches is known. This ratio can be obtained from the gain saturation of the SOA (fig. 2). Using this the output power distribution (for $\Delta\Phi_L=\pi/2$, as required for the combiner) is given in fig. 5 as a function of the input power.

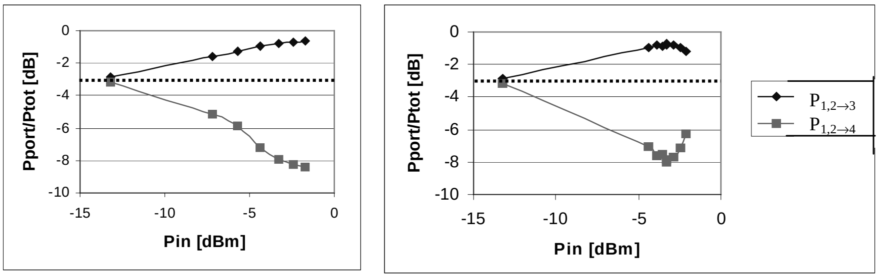

***Fig. 5**: Relative power from the two output ports of the combiner. For both measured series a maximum of 85% of the power is guided to port 3, on injection in either of the two input ports. For comparison, the dotted line indicates the -3-dB loss of a passive combiner.*

For both measurements the on/off ratio over the output ports is 7.2 dB (i.e., 85 % of the signal comes from the desired port). This is actually better then what can be derived from eqs.(2), with x=0.1. The reason is that due to the gain saturation the powers from the two branches of the interferometer become more equal, so that a more complete interference effect is obtained.

Conclusions

A self-routing optical combiner has been demonstrated for the first time. It guides about 85% of the signal from each of two input ports to the same output port. The combiner is made with off-the-shelf components: fibers, fused fiber couplers and SOAs. The non-linear switching is obtained with carrier depletion in SOAs. With the SOAs used here an input power of around 0.5 mW (-3 dBm) is needed for the optimal operation of the device.

The non-linear operation of the combiner is determined with a measurement procedure suited to circumvent stability problems. The procedure involves periodic switching between the two input ports of the combiner. Since non-linear and linear phase shifts react differently to the switching this allows unambiguous determination of the non-linear effect. The instability of the combiner indicates that integrated optical realizations are preferable. It is known from wavelength converters that integrated Mach-Zehnder structures are very stable [4].

References

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