A Mach-Zehnder-interferometer-based low-loss combiner

A Mach–Zehnder-Interferometer-Based Low-Loss Combiner

J. J. G. M. van der Tol, H. de Waardt, and Y. Liu

Abstract—**Passive optical combiners have an unwanted 3-dB loss. This is avoided with optical switches, but these need control functions to synchronize with the optical signals. A nonlinear Mach–Zehnder interferometer can provide the combiner function without control signals. In the experiment reported here, this combiner was realized with a fiber component. Semiconductor optical amplifiers (SOAs) acted as the nonlinear phase shifting elements. Thus a proof-of-principle for the self-routing combiner is obtained: optical signals on either of the two input ports are guided to one and the same output port without any control mechanism in the interferometer. The nonlinear effect used is self-phase modulation, caused by carrier depletion in the SOAs as they approach saturation. The optical power at which the nonlinear switching occurred was about −2 dBm. The residual combiner loss was only 0.7 dB.**

Index Terms—**Interference, measurement, nonlinear optics, optical couplers, optical fiber devices, optical signal processing, semiconductor optical amplifiers.**

I. Introduction

AN ESSENTIAL function in optical networks is the combining of optical signals. This is required in, e.g., fiber trees, as used in passive optical network (PON) systems. Usually the combiner is a passive function, obtained with fused fiber couplers or planar Y-junctions. These have, however, an inherent 3-dB loss. Optical switches avoid this, but require control functions to synchronize with the optical signals.

A better solution is a nonlinear optical device [1], in which the signals themselves set their optical path. Such a nonlinear combiner should mimic characteristics of the passive couplers. In particular, it should have (at least) two inputs and one output, it should treat the input signals equally, operate without control signals, and allow for a large range of bit rates from continuous wave (CW) up to as high as possible. Previous nonlinear switches do not conform to these demands, they use, e.g., control pulses [2]. Nonlinear optical loop mirrors (NOLM) [3] can perform self-switching (on/off switching) between two ports, but these devices are operating with optical pulses, and are therefore, limited to certain pulse formats. This is undesirable for the combiner function as defined above. The combiner proposed in [1] is a Mach–Zehnder interferometer (MZI), in which unequal optical powers in the branches give nonlinear phase shifts. Incomplete interference then gives a small penalty, e.g., if the power ratio over the branches is 3:1, this results in only 0.3-dB loss. Just as with passive couplers, two signals (of identical wavelength) are not allowed at the same time on the inputs, otherwise the operation is disturbed. Multiple signals will interfere and cause crosstalk and signal degradation. Applications like PON systems [4], therefore, include a time-division access protocol, allowing only one signal at one time. This letter describes a proof of principle of the new low-loss nonlinear combiner with fiber-based off-the-shelf components. Semiconductor optical amplifiers (SOAs) are used as nonlinear elements.

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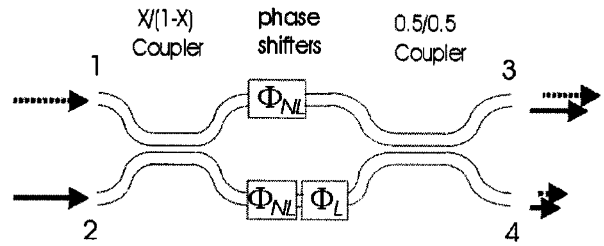

Fig. 1. The fiber-based nonlinear combiner. The nonlinear phase shift in the arms of the Mach–Zehnder structure is given by $\Phi_{\rm NL}$. The linear phase shift $\Phi_{\rm L}$ results from length differences between the arms.

II. Device Concept

The interferometer contains two couplers and two nonlinear phase shifters (Fig. 1). The output coupler is a 0.5/0.5 coupler, however, the input coupler is unbalanced with a coupling ratio of $x/(1-x)$. This leads to an unequal power distribution in the branches of the interferometer, and therefore, to a nonlinear phase shift difference $\Delta\Phi_{\rm NL}$. Together with a linear phase shift difference $\Delta\Phi_{\rm L}$, this determines the output powers. $\Delta\Phi_{\rm NL}$ changes sign with input port, since the highest optical power is in the opposite branch. In contrast, $\Delta\Phi_{\rm L}$ is independent of the input used. The output powers for the different paths through the circuit are with unit input power

$$P_{i\to j} = 0.5 - (-1)^{i+j}\sqrt{x(1-x)} \times \cos\left((-1)^{i+1}\Delta\Phi_{\rm NL} + \Delta\Phi_{\rm L}\right) \quad (1)$$

for the path between input $i\ (=1,2)$ and output $j\ (=3,4)$. If both $\Delta\Phi_{\rm NL}$ and $\Delta\Phi_{\rm L}$ are equal to $\pi/2$ for $j=3$, this reduces to

$$P_{1\to 3} = P_{2\to 3} = 0.5 + \sqrt{x(1-x)} \quad (2)$$

The output powers no longer depend on the input port. Both input signals are, for the largest part, transferred to output port 3. In this way, the combiner function is obtained. The value of x is a compromise between the acceptable incompleteness of

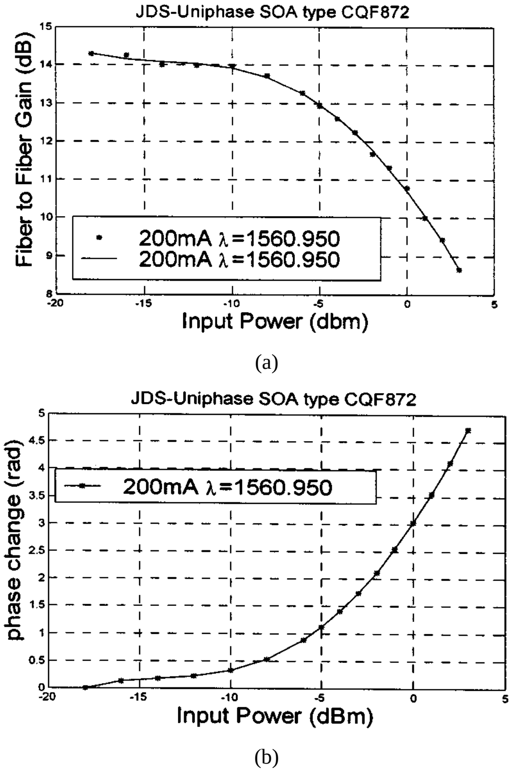

Fig. 2. (a): Gain saturation measured for the SOAs used in the combiner. (b): Phase change versus input power, as derived from the gain saturation.

the interference, and the required power difference for sufficient $\Delta\Phi_{\mathrm{NL}}$.

III. SOA-Characterization

Optically induced phase shifts are obtained in SOAs with carrier depletion. The reduction of free carrier concentration in SOAs at high enough input powers increases the refractive index, and thus, results in a phase shift.

From the gain saturation of the commercially obtained SOAs [see Fig. 2(a)] the phase change in the SOA is derived [see Fig. 2(b)], with the measured linewidth enhancement factor of 7.2. For an input power difference of 9.5 dB at the SOAs as applied in the experiment, $\Delta\Phi_{\mathrm{NL}} = \pi/2$ is expected for -1.5 dBm input power in the MZI.

Since the SOAs are in saturation, the power ratio at the output coupler of the MZI is different from the coupling ratio of the input coupler. It will be closer to one, because the highest power experiences the lowest gain. This is beneficial, because interference is then less incomplete. Saturation can be described by a simplified model [6]

$$P_{\mathrm{out}} = P_{\mathrm{in}} \frac{G_0}{1 + \left(\frac{p_{\mathrm{in}}}{P_{\mathrm{sat}}}\right)^n} \tag{3}$$

where

- P_{sat} saturation power;
- G_0 small signal gain;
- n a parameter which needs to be fitted to the measured saturation curve.

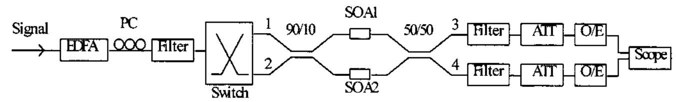

Fig. 3. The experimental setup. PC: Polarization Controller. BPF: Bandpass filter. ATT: Attenuator. O/E: Optoelectronic converter. The numbers 1, 2 and 3, 4 indicate the input and the output ports of the low-loss combiner.

Corrected values for the parameter x in (1) and (2) can be derived from this

$$x_c = 0.5 \frac{x\left(1 + \left[\frac{(1-x)P_{\mathrm{in}}}{P_{\mathrm{sat}}}\right]^n\right) - (1-x)\left(1 + \left(\frac{xP_{\mathrm{in}}}{P_{\mathrm{sat}}}\right)^n\right)}{x\left(1 + \left[\frac{(1-x)P_{\mathrm{in}}}{P_{\mathrm{sat}}}\right]^n\right) + (1-x)\left(1 + \left(\frac{xP_{\mathrm{in}}}{P_{\mathrm{sat}}}\right)^n\right)} + 0.5 \tag{4}$$

IV. Experimental Procedure

In the experimental setup (Fig. 3), stability is an issue. Due to environmental influences, the value of $\Delta\Phi_{\mathrm{L}}$ drifts during the experiment, influencing the output power distribution. Therefore, a measurement procedure is needed that determines unambiguously $\Delta\Phi_{\mathrm{NL}}$. This is achieved with an optical switch that alternates the signal between the input ports. The frequency (100 Hz) is high enough to neglect drift in one switching period. The power difference from the output ports then shows a periodic pattern. It slowly changes in amplitude, due to the environmental drift. For $\Delta\Phi_{\mathrm{L}} = 0$ and $\Delta\Phi_{\mathrm{L}} = \pi$, the maximum amplitude A_{max} is obtained

$$A_{\mathrm{max}} = 4\sqrt{x_c(1-x_c)}\left[\cos(\Delta\Phi_{\mathrm{NL}})\right] \tag{5}$$

where A_{max} is determined by observing the output power distribution. For operation as a combiner ($\Delta\Phi_{\mathrm{NL}} = \pi/2$), it becomes zero and the periodic pattern in the output disappears. Switching between the input ports then has no influence. The environmental drift shows up as a slow variation of the output power distribution. With $\Delta\Phi_{\mathrm{L}} = \pi/2$, light from both input ports is primarily guided to port 3.

An erbium-doped fiber amplifier (EDFA) supports a large range of input powers at the combiner. Optical bandpass filters eliminate the ASE. Attenuators are used to avoid saturation in the detection. Detection is done with homemade optoelectronic converters. The unbalanced coupler in the MZI is a 0.9/0.1 coupler (so $x = 0.1$). Experiments are done at 1560.95 nm (ITU-wavelength), determined by the available filters. The SOAs are electrically powered with 200 mA.

V. Results

Fig. 4(a) shows A_{max} as a function of input power into the MZI. A_{max} vanishes at 0.47 mW (-3.3 dBm). At this value, the optimal combiner function is found. This verifies that indeed an optically induced phase shift is occurring, which results in a combiner: both input signals (from port 1 or 2) are guided to the same output.

Due to the drift, the combiner operation is only directly observable if $\Delta\Phi_{\mathrm{NL}}$ is close to $\pi/2$. It can, however, be derived from A_{max} and from the gain saturation of the SOA

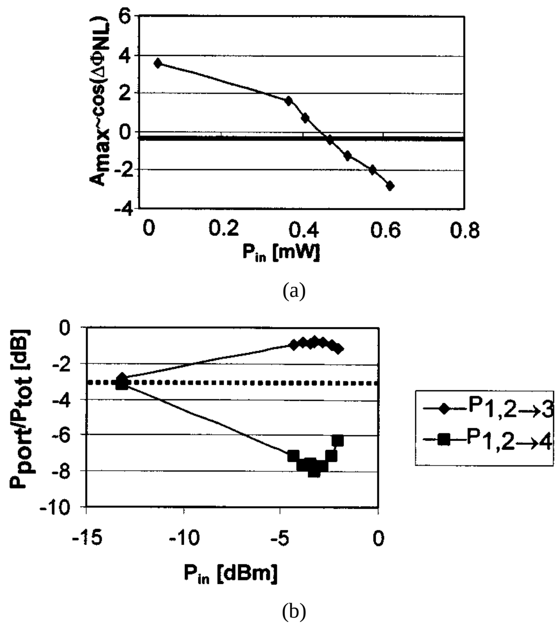

Fig. 4. (a) Maximum output power difference for injection in the two input ports 1 and 2. For a zero value both signals from port 1 and from port 2 are guided to the same output port. (b) Relative power from the two output ports of the combiner. A maximum of 85% of the power is guided to port 3, on injection in either of the two input ports. The dotted line indicates the 3-dB loss of a passive combiner.

[see Fig. 2(a)]. The output power distribution is given in Fig. 4(b) as a function of the input power.

The on/off ratio over the output ports is 7.2 dB. The fraction of the signal from the desired port is 85%, so combiner loss is 0.7 dB.

VI. Conclusion and Discussion

A self-routing optical combiner is demonstrated for the first time. It guides 85% of the signal from each of two inputs to the same output. The combiner is made with the following off-the-shelf components: fibers, fused fiber couplers, and SOAs. Nonlinear switching is obtained with carrier depletion in SOAs at an input power of around 0.5 mW (−3 dBm). The device is power dependent, but combiner loss below 3 dB is expected over a power range of at least 10 dB. The signal-to-noise (SNR) performance of the combiner should be compared with a passive coupler in combination with an inline SOA. If this SOA is in the output port, the noise produced is equal to the noise from the two SOAs in the MZI, since the output coupler of the MZI reduces this noise by 3 dB. The reduction of the combiner loss, therefore, implies a 2.3-dB increase in SNR. A better SNR can be obtained with SOAs in each of the input lines of a passive combiner with one SOA turned off. This requires on/off switching of these SOAs according to which input port is used. The combiner should avoid such control requirements. The high bit-rate behavior of the combiner has not been tested. It has been demonstrated, however, that comparable MZI structures with SOAs, aimed at 2R-regeneration, can handle bit rates as high as 40 Gb/s [5]. This suggests that very high-speed operation of the combiner is, in principle, possible.

The fiber-based combiner showed unstable behavior. One can think of stabilization schemes to solve this, but this runs counter to the desired simple implementation of a combiner. Therefore, it is preferred to use integrated optical planar realizations for the combiner, which have shown to be stable [5].

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