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An Optical Combiner with Low Loss

Introduction

Optical fiber is becoming the dominant transmission medium for communication services. These developments put an increasing demand on the optical hardware used in fiber networks. An essential function in these networks is the combining of optical signals. Usually this is a passive function, obtained with fused fiber couplers or planar splitters. 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 optical signals.

This proposal aims at solving this dilemma with a non-linear optical device, in which the appearance of the signals themselves sets the optical path. Previously proposed non-linear switches suitable for a combiner function use either control pulses (e.g. a 2-to-2 Mach-Zehnder interferometer [1]), or are non-interferometric, (e.g. adiabatic switches [2]), and therefore require large non-linear (NL) effects. For the combiner proposed here (see fig. 1) a 1-to-2 circuit is needed and no control pulses are allowed. Furthermore, interferometric devices are preferred, since these use phase shifts, which can be large even with small NL effects, if the interaction length is long enough.

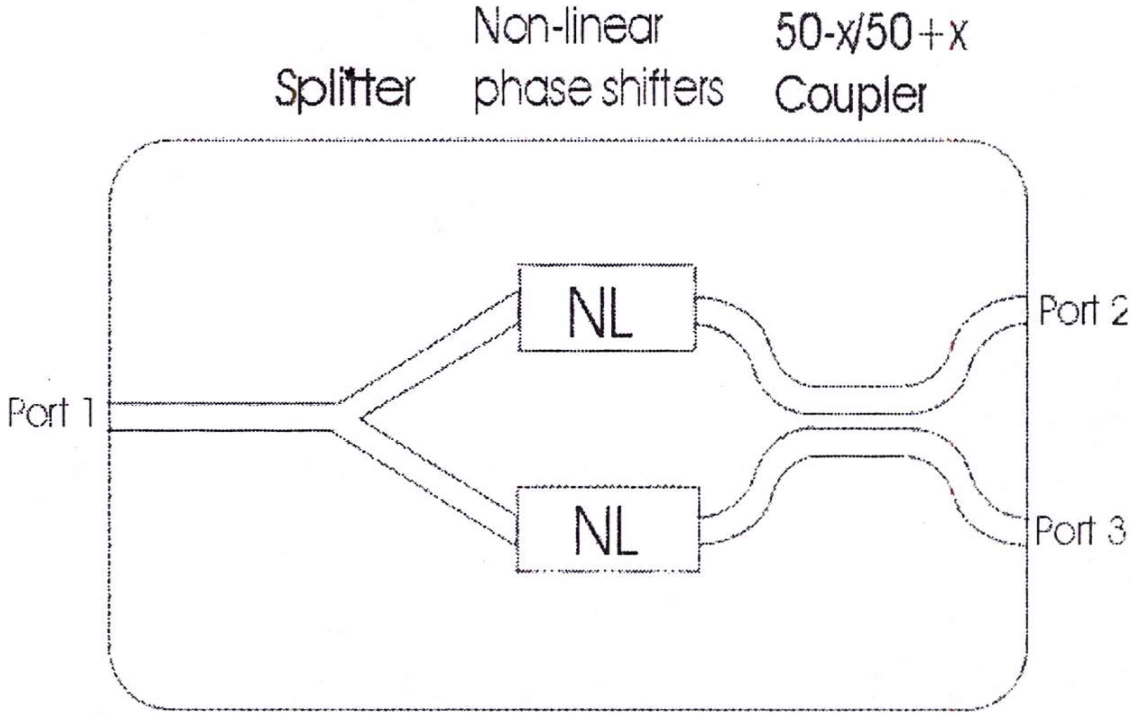

Fig. 1. Layout of the nearly loss-less combiner. "NL" indicates a non-linear phase shifting section, "50-*x*/50+*x*" the coupling ratio of the 2-by-2 coupler

Concept of the device

The 1-to-2 device (see fig. 1) operates as a splitter in one direction. In the other direction it functions as a (nearly) loss-less combiner. The device is a Mach-Zehnder interferometer, with non-linear phase shifters in the branches. A 1-to-2 splitter and a 2-by-2 coupler, with a coupling ratio different from 50%, are used in the interferometer.

The operation is as follows: If light is applied via port 1 the symmetry of the circuit results in two equal output signals at ports 2 and 3. For light injected in port 2 the situation is different. This signal is unequally distributed over the two branches of the MZ-interferometer, because of the coupler asymmetry. Furthermore, there is a fundamental 90°-phase difference between the signals from the coupler. In the non-linear sections the refractive index is intensity dependent. The unequal intensities then lead to different phase shifts in the branches. A phase difference of 90° is required, to compensate the coupler induced phase difference. The two signals from the branches will positively interfere and optimally recombine at port 1. Using port 3 instead of 2 merely mirrors the situation; both the non-linear and the coupler induced phase shifts occur in the other branch, and so again compensate each other. The coupler asymmetry, should be large, to limit the length of the NL sections.

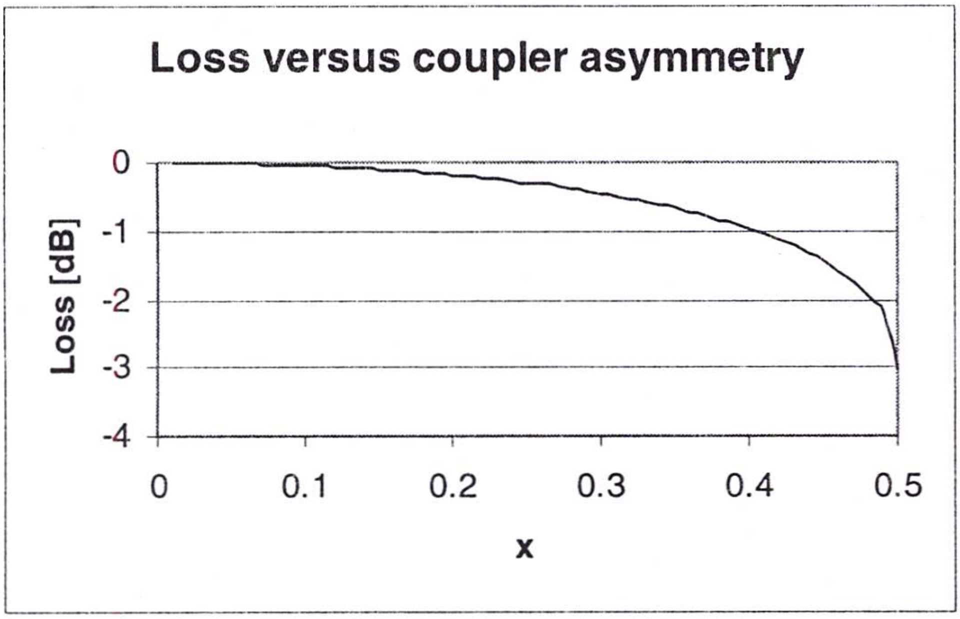

Fig. 2. Loss of the combiner as a function of the coupler parameter x. Note that for x close to zero the powers in the branches are nearly equal, so that the length of the NL sections must be extremely large. For x equals 0.5 all power is injected in one branch, so that no interference is left and the loss of a passive combiner is obtained [3]

A complication is that, because of the unequal powers in the branches, no complete reconstruction of a fundamental mode (which is guided by the splitter towards port 1) is possible. Consequently, some of the power is radiated out. This loss depends on the asymmetry parameter x (see fig. 2). Its value should be maximized, but is limited by this loss. The graph shows that even for relatively large values of x the loss is small, e.g. 0.3 dB at $x = 0.25$, to be compared with the 3 dB loss of a passive combiner. Hence the term "nearly loss-less combiner". For $x = 0.25$ the powers in the branches differ by a factor of 3, so that an efficient use of the NL effect is made.

The NL effect is proportional to the optical power, so consequently the combiner is power dependent (see fig. 3). A reduction of power by a factor of two from the optimal value results in an extra loss of –0.9 dB, which still is a sizable improvement over a passive combiner. On the other hand, an increase of a factor of 2 results in -3 dB extra loss. This means that increases in power should be closely controlled. To achieve a high tolerance for power variations, the operational power could be chosen somewhat below the optimum power, e.g. at 40% (–4 dB). The loss of the combiner is then a little higher at the operational power (1 dB), but the power range for a loss lower than that of a passive combiner is in that case approximately 12 dB.

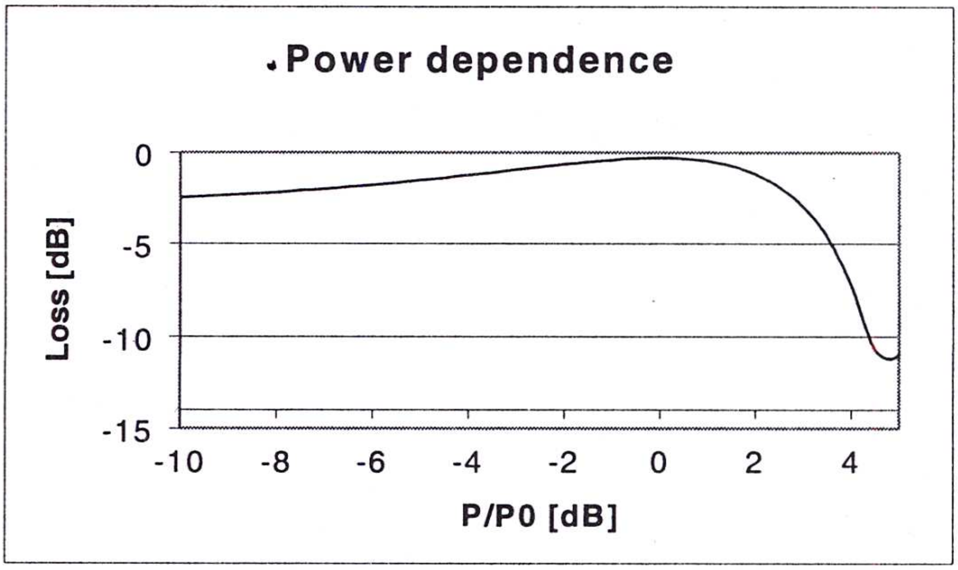

Fig. 3. Loss of the combiner as a function of optical power for the coupler parameter x equal to 0.25. P0 indicates the optimum power for the device. Note that for low powers the NL effect vanishes and the 3 dB loss of a passive combiner is obtained [3]

Applications

Combiners are needed in a wide variety of optical transmission systems. These differ in the time response that is required. The applications of the combiner are therefore determined by the dynamics of the NL effect. The following applications are possible:

- Protection: An optical protection system can be implemented with two optical links, connected at one side to a transmitter with a 1-to-2 switch, at the other side to a receiver with a combiner. If a fiber breaks the switch selects the intact link. The nearly loss-less combiner avoids a 3-dB loss on both links. The reaction time is related to that of electrical protection (50 ms), so that the NL effects can be slow.
- Passive Optical Network (PON). This consists of a fiber tree to connect users to a local exchange. Splitter stages are used with 3-dB loss. This is unavoidable in the direction to the subscribers, since a signal has to be distributed. In the other direction optical power is needlessly lost, so that high-power lasers are used at the subscriber side. The combiner proposed here lowers the loss, making much cheaper lasers feasible. In a PON the access mechanism prevents collision of optical signals. The time scale is determined by this access mechanism, with timeslots of a few μs.

- Bit reshaping. The extinction ratio of an optical bit pattern is improved by transmission trough the combiner (from the 2-port to the 1-port side), because the central part, with high intensity, experiences lower loss than the flanks (c.f. fig. 3). In this application the response must be faster than the bit time, which is below 1 ns.
- Optical Time Division Multiplexing (OTDM). This is a technique to obtain very high bitrates over a fiber, by merging pulse trains with a combiner. The aim is to achieve bitrates in the order of 100 Gb/s. To use the combiner proposed here, in order to reduce the optical loss, the reaction time must be in the picosecond range.

In all of these applications the combiner provides an improvement in the power budget. A limitation is however that no simultaneous signals at both ports of the 2-port side are allowed. This means, e.g., that use as a WDM-multiplexer requires bit synchronization.

Implementation

The proposed combiner can be implemented in a number of ways. It is possible to use polymeric waveguides, in which the NL effect is obtained by locally absorbing a fraction of the optical power. The large thermo-optic effect in polymers results then in a power dependent refractive index change [4]. This mechanism is slow (ms range), so that only application in a protection system is relevant.

The preferred implementation of the combiner is with the InP-based material system. This material is important for applications in telecommunications. The components in the circuit can readily be made in InGaAsP/InP. Splitters have been realized many times in this material [5]. The asymmetric coupler can be made with a directional coupler, with a suitable interaction length. The real challenge is the realization of the NL sections.

Because the device is an interferometer small NL effects can be used with sufficiently long phase shifting sections. Several possibilities exist to obtain NL effects. These effects are notoriously small in most materials. In III/V semiconductor quantum wells however relatively large effects have been found. This is attributed to changes in bandgap energies due to the presence of an optical field. Mechanisms that play a role here are band filling, quantum confined Stark effect and exciton bleaching [6]. Because changes in absorption reflect themselves in the refractive index through the well-known Kramers-Kronig relations, a third-order non-linear effect (Kerr-effect) is obtained. The non-linear coefficient in InP-based materials can be as high as 10^{-6} cm^2/W [7]. This implies a length of the non-linear sections of 700 microns with an input power of 0.1 mW. However, the application of these effects often encounters serious difficulties, because they show an unusable combination of absorption and refraction. In that case an alternative solution can be found, by using carrier depletion in a semiconductor optical amplifier [8]. This is a well-known and large effect to obtain non-linear phase shifts. The combiner then requires a power supply, and is no longer a stand-alone device.

One of the promising effect here will be a using of the photoinduced effects in the chalcogenide glasses [9,10]. This is of especial interest for creation of the high-response devices.

Conclusions and further plans

The proposed device will improve the power budget in optical networks. It removes a fundamental loss of 3 dB experienced by optical signals in combiners based on passive splitters and couplers, without the need for additional control, as required for thermo-optic and electro-optic switches. Depending on the speed that can be realized applications include optical protection, PONs, reshaping of bits and OTDM.

The combiner will be realized in InGaAsP/InP, the material of choice for application in telecommunications at 1.55 μm. It is anticipated that this component occupies a surface of less than 0.5 mm^2, allowing mass production and low manufacturing costs. The component can be integrated with other planar components.

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Summary

Optical splitters give an unwanted 3dB loss when used as combiners. This is avoided with optical switches, but these need control functions to synchronize with the optical signals. The device proposed here provides a combiner function without control signals. It uses a nonlinear Mach-Zehnder interferometer in a 1-to-2 port configuration, operating as a splitter in one direction and as a self-routing combiner in the other. Depending on how fast the nonlinear effect is, applications can be found in protection, passive optical networks, bit reshaping or optical time division multiplexing. The self-phase modulation in semiconductor optical amplifiers on InP is one option for a sufficiently large nonlinear effect.