All-fiber 90° optical hybrid for coherent communications

Leonid G. Kazovsky, Lyn Curtis, William C. Young, and Nim K. Cheung

A 90° optical hybrid is a four-port optical device with two inputs and two outputs. The two output signals are proportional to $\mathbf{E}_1 + \mathbf{E}_2$ and $\mathbf{E}_1 + \mathbf{E}_2 \exp(j90°)$, respectively, where $\mathbf{E}_1$ and $\mathbf{E}_2$ are the complex amplitudes of the two input signals. The 90° hybrids are needed in many applications, including homodyne optical receivers in both phase-locked and phase-diversity configurations. In this paper, the principle of operation of an all-fiber 90° hybrid is described, and an experimental unit using connectorized in-line single-mode fiber components is reported.

I. Introduction

A 90° optical hybrid is a four-port optical device with two inputs and two outputs. The two output signals are proportional to $\mathbf{E}_1 + \mathbf{E}_2$ and $\mathbf{E}_1 + \mathbf{E}_2 \exp(j90°)$, respectively, where $\mathbf{E}_1$ and $\mathbf{E}_2$ are the complex amplitudes of the two input signals. The 90° hybrids are needed in many applications, including homodyne optical receivers in both phase-locked[1,2] and phase-diversity[3,4] configurations. In phase-locked homodyne receivers employing nonlinear phase-locked loops,[1,2] the loop locks the local oscillator in quadrature to the received signal at one of the hybrid outputs (say, output x). As a result, the local oscillator signal and the received signal appear in phase at the other hybrid output (say, output y), where the data detector is connected. In phase-diversity homodyne receivers,[3,4] the two outputs x and y are proportional to $A \cos\phi$ and $A \sin\phi$, respectively, where A is the signal amplitude and ϕ is the signal phase. A phase-diversity receiver estimates the signal power by calculating $x^2 + y^2$, a quantity independent of ϕ. The 90° hybrids can be implemented integrally in electrooptic crystals,[1] built with discrete optical components,[5] or implemented entirely in the fiber domain.[6] An optical hybrid implemented in the single-mode fiber domain is particularly attractive since it is fully compatible with other components of a single-mode fiber communication system, and the high insertion loss and alignment problems associated with the conventional bulk optic components can be avoided. In this paper, the principle of operation of an all-fiber 90° hybrid is described, and an experimental unit using connectorized in-line single-mode fiber components is reported.

II. Principle of Operation

Figure 1 shows a block diagram of an all-fiber hybrid and indicates the notation. The device operates as follows. The two input signals are assumed to be identically linearly polarized. Hence the complex vector electric fields at input 1 and input 2 are, respectively,

$$\mathbf{E}_1 = E_1[1 \quad 0]^T, \tag{1}$$

$$\mathbf{E}_2 = E_2 \exp(j\Phi)[1 \quad 0]^T, \tag{2}$$

where E_1 and E_2 are the scalar amplitudes of the signals at the two input ports, Φ is the relative phase between the two inputs (input 1 is selected as the phase reference); and $[\quad]^T$ denotes transposition. Equations (1) and (2) and the rest of the paper employ the Jones polarization matrix calculus[7] describing the electric field with an arbitrary state of polarization (SOP) by a (generally complex) vector consisting of two spatially orthogonal components. Polarization controller 1 rotates the SOP by 45°, while polarization controller 2 converts the linear SOP into a circular SOP:

$$\mathbf{E}_3 = \frac{1}{\sqrt{2}} E_1[1 \quad 1]^T; \tag{3}$$

$$\mathbf{E}_4 = \frac{1}{\sqrt{2}} E_2 \exp(j\Phi)[1 \quad \exp(j\Theta)]^T, \tag{4}$$

where $\Theta = 90°$. Assume the coupling coefficient of the 3-dB coupler to be polarization independent. Then the output signals of the 3-dB coupler are, respectively,

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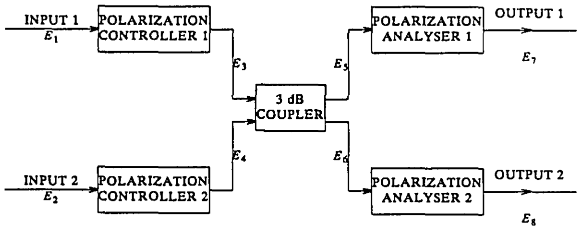

Fig. 1. Block diagram of an all-fiber optical 90° hybrid.

$$\mathbf{E}_5 = \frac{1}{\sqrt{2}}\mathbf{E}_3 + \frac{1}{\sqrt{2}}\mathbf{E}_4 \exp(j90°)$$

$$= 0.5\begin{bmatrix} E_1 + E_2\exp[j(\Phi + 90°)] \\ E_1 + E_2\exp[j(\Phi + \Theta + 90°)]\end{bmatrix}, \quad (5)$$

$$\mathbf{E}_6 = \frac{1}{\sqrt{2}}\mathbf{E}_3 \exp(j90°) + \frac{1}{\sqrt{2}}\mathbf{E}_4$$

$$= 0.5\begin{bmatrix} E_1\exp(j90°) + E_2\exp(j\Phi) \\ E_1\exp(j90°) + E_2\exp[j(\Phi + \Theta)]\end{bmatrix}. \quad (6)$$

The components of the hybrid are interconnected with a conventional (*not* polarization-preserving) single-mode fiber; see Sec. III for fiber specifications. The beat length for a conventional unstrained single-mode fiber is around 50 m, while the length of interconnecting pigtails in Fig. 1 is several centimeters. Therefore, the polarization states at the inputs of the polarization analyzers are essentially the same as the polarization states at the outputs of the 3-dB coupler. Since the polarization analyzers are aligned orthogonally with respect to each other, their outputs are

$$\mathbf{E}_7 = 0.5\begin{bmatrix} E_1 + E_2\exp[j(\Phi + 90°)] \\ 0\end{bmatrix}, \quad (7)$$

$$\mathbf{E}_8 = 0.5\begin{bmatrix} 0 \\ E_1\exp(j90°) + E_2\exp[j(\Phi + \Theta)]\end{bmatrix}$$

$$= 0.5\exp(j90°)\begin{bmatrix} 0 \\ E_1 + E_2\exp[j(\Phi + \Theta - 90°)]\end{bmatrix}. \quad (8)$$

For the 90° hybrid, $\Theta = 90°$, and Eq. (8) yields

$$E_8 = 0.5\exp(j90°)\begin{bmatrix} 0 \\ E_1 + E_2\exp(j\Phi)\end{bmatrix}. \quad (9)$$

Comparison of Eq. (7) with Eq. (9) reveals that the device of Fig. 1 should operate as a 90° hybrid with a 3-dB intrinsic loss.

III. Implementation

Figure 2 shows a photograph of an experimental hybrid built in our laboratory. The device is mounted on a 30 × 60-cm (1 x 2-ft) board and consists of two single-mode fiber-coil-type polarization controllers,[8] one 3-dB fused biconical coupler,[9] and two polarization analyzers built with single-mode fiber and birefringent crystals.[10] (The coupling coefficient of the 3-dB coupler was experimentally found to be polarization independent.) All the fibers used in this experiment are single-mode 9-μm core 125-μm o.d. depressed-cladding-index fibers with 50-m beat length. All the components are interconnected with precision-ground biconic connectors.[11]

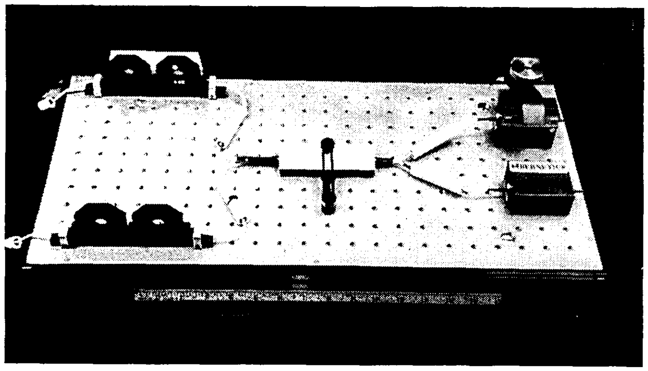

Fig. 2. Experimental 90° hybrid.

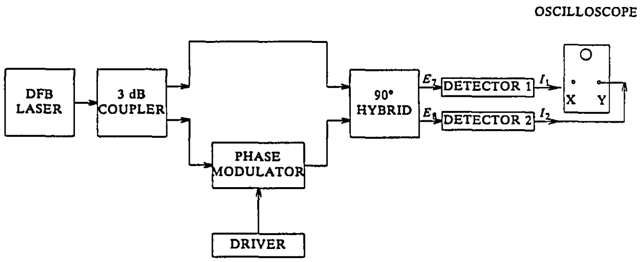

Fig. 3. Simplified block diagram of an experimental setup used to verify the properties of a 90° hybrid.

IV. Performance

The excess loss of the device has been measured to be 2 dB in addition to the intrinsic 3-dB loss. The rather high excess loss is due to the three devices (polarization controller, 3-dB coupler, and polarization analyzer) and four connectors encountered by each of the two input signals.

To verify the phase properties of the device, the experimental setup shown in Fig. 3 has been constructed. The two input signals of the hybrid were derived from a single-frequency DFB laser, and the relative phase Φ was introduced with a phase modulator. The output currents of the detectors are, respectively,

$$I_1 = R|\mathbf{E}_7|^2 = 0.25R[E_1^2 + E_2^2 + 2E_1E_2\cos(\Phi + 90°)], \quad (10)$$

$$I_2 = R|\mathbf{E}_8|^2 = 0.25R(E_1^2 + E_2^2 + 2E_1E_2\cos\Phi). \quad (11)$$

Equations (10) and (11) show that the plot I_1 vs I_2 should be a circle if the hybrid operates ideally. Figure 4 shows an experimental plot of I_1 vs I_2 displayed on the oscilloscope of Fig. 3. Inspection of Fig. 4 reveals that the hybrid operates nearly ideally.

V. Conclusions

An all-fiber 90° optical hybrid has been designed, built and tested. The device has an excess loss of 2 dB and exhibits nearly ideal behavior predicted by Eqs. (10) and (11). The same principle can be used to create an arbitrary phase relationship between the two outputs. The applications of the device include ho-

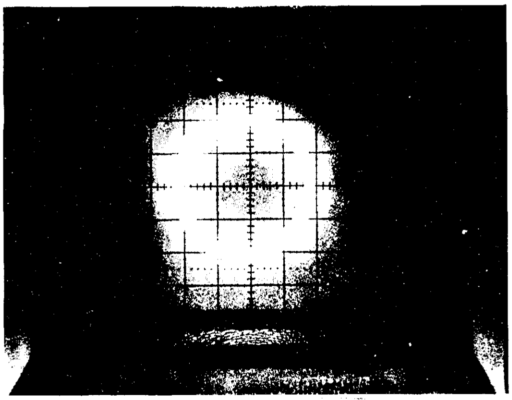

Fig. 4. Experimentally measured plot of I_1 vs I_2 conforming the operation of the 90° hybrid.

modyne optical receivers in both phase-locked and multiport configurations.

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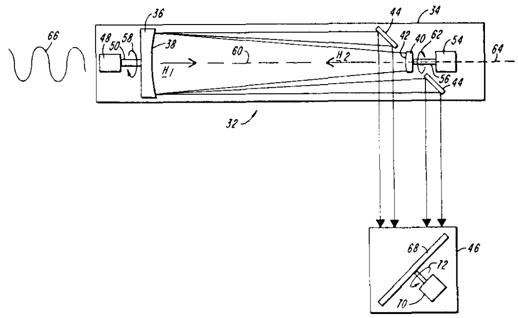
Patents *continued from page 417*

4,580,270 1 Apr. 1986 (Cl. 372–107)

High-energy laser system having gyroscopically stabilized optical elements.

W. M. JOHNSON, M. S. WEINBERG, and R. CARROLL. Assigned to The Charles Stark Draper Laboratory, Inc. Filed 8 July 1983.

This patent claims that laser cavities can be made more insensitive to vibration-induced misalignment if the mirrors (42 in the figure) are mounted on rapidly spinning rotors. Besides the gyroscopic stabilization, this spinning cools the mirror by convection. G.D.

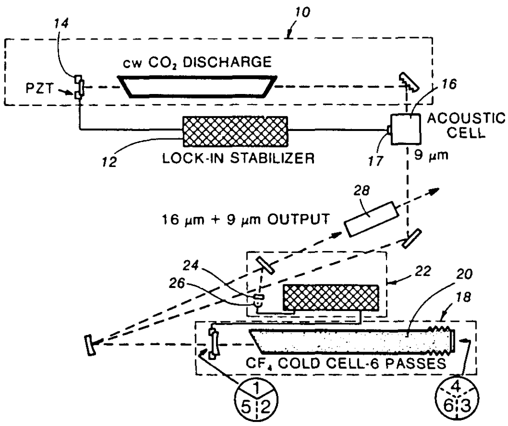


4,599,726 8 July 1986 (Cl. 372–4)

Apparatus and method for generating continuous wave 16 *M* laser radiation using gaseous CF_4.

J. M. TELLE. Assigned to U.S.A. as represented by U.S. Department of Energy. Filed 1 May 1984.

This patent describes a laser-pumped laser capable of cw outputs at wavelengths near 16 μm. A 9-μm CO_2 laser pumps a cell of cold CF_4 (see figure). The spectral distribution from the CO_2 laser is controlled so as to be efficiently absorbed by the CF_4. G.D.



4,599,727 8 July 1986 (Cl. 372–41)

Strontium aluminum fluoride laser.

H. P. JENSSEN. Assigned to Massachusetts Institute of Technology. Filed 26 Oct. 1984.

Chromium-doped strontium aluminum fluoride is an optically pumped laser material that lases in a broad wavelength band centered near 850 nm. Its cross section for stimulated emission is approximately twice those of chromium in alexandrite or emerald. G.D.

4,606,031 12 Aug. 1986 (Cl. 372–28)

Device for frequency modulation of a laser output spectrum.

J. R. BEENE and C. E. BEMIS, JR. Assigned to U.S.A. as represented by the U.S. Department of Energy. Filed 17 July 1984.

In many laser spectroscopy applications the desired laser frequency is unobtainable because it falls between two adjacent longitudinal modes. By rapidly and sinusoidally altering the cavity length (mirror position) at least one-half wavelength, the mode frequencies will sweep out the continuum of the gain profile. In one preferred embodiment, the high-frequency trapping filter is removed from a commercial piezoelectric transducer, which then is operated at one of its mechanical resonances. G.D.