US 20030169964A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2003/0169964 A1

Wang et al. (43) Pub. Date: Sep. 11, 2003

(54) **POWER SPLITTER/COMBINER WITH PARAMETER TOLERANCE AND DESIGN PROCESS THEREFOR**

(76) Inventors: **Tairan Wang**, Brighton, MA (US); **James S. Foresi**, Waltham, MA (US)

Correspondence Address:
Attn: Matthew E. Connors
Samuels, Gauthier & Stevens, LLP
Suite 3300
225 Franklin Street
Boston, MA 02110 (US)

(21) Appl. No.: **10/093,663**

(22) Filed: **Mar. 8, 2002**

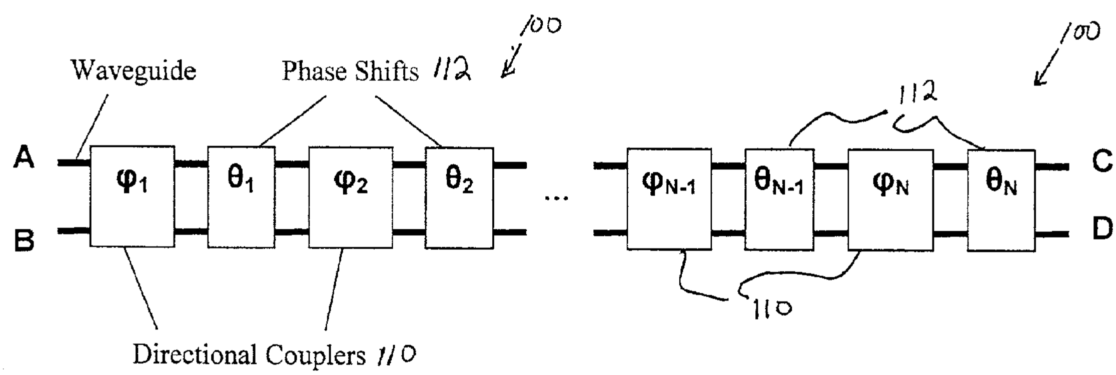
Publication Classification

(51) **Int. Cl.**[7] **G02B 6/26**

(52) **U.S. Cl.** **385/27**

(57) **ABSTRACT**

A splitter/combiner that is highly tolerant to parameter deviations as a result of fabrication errors, for example, which might otherwise create undesirable frequency dependency and polarization dependency. It is specifically applicable to integration into the transmission and/or reflection light paths of systems. In this power splitter/combiner system, each splitter/combiner is comprised of two or more directional couplers serially connected to two or more phase shifts in an alternating order (i.e., directional coupler, phase shift, directional coupler, phase shift, directional coupler). The invention addresses the problem of parameter deviations in splitter/combiners by connecting multiple directional couplers and multiple phase shifts and selecting specific coupling and phase values for the directional couplers and phase shifts to minimize the impact of parameter changes on the output signal. The invention also addresses the problem of differential deviations in parameters by providing tunable phase shifts employing controlled effects, such as electro-optic or thermo-optic refractive index changes.



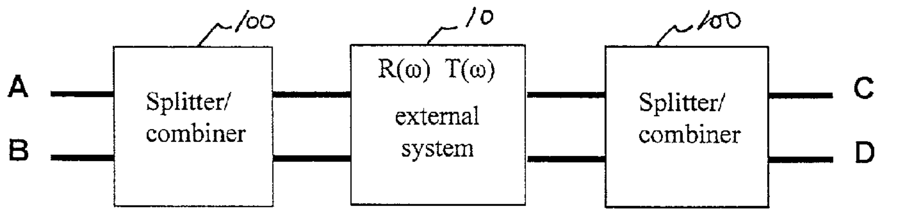

100
10
100
A
B
Splitter/
combiner
R(ω) T(ω)
external
system
Splitter/
combiner
C
D

FIG. 1

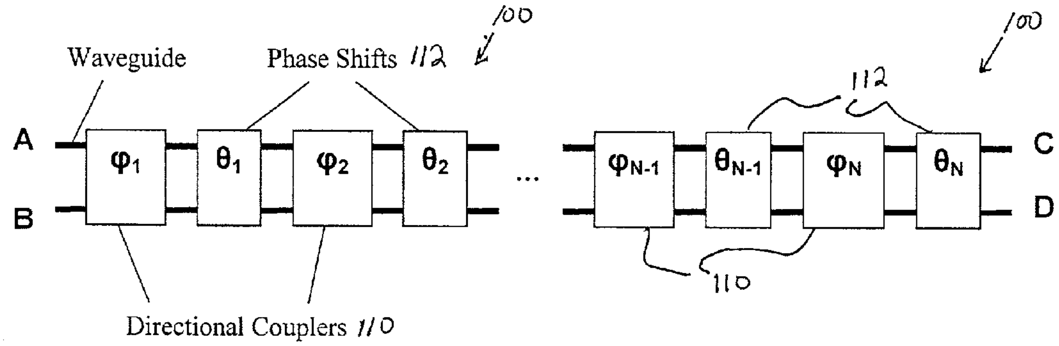

Waveguide
Phase Shifts 112
100
100
112
A
B
φ1
θ1
φ2
θ2
...
φN-1
θN-1
φN
θN
C
D
Directional Couplers 110
110

FIG. 2

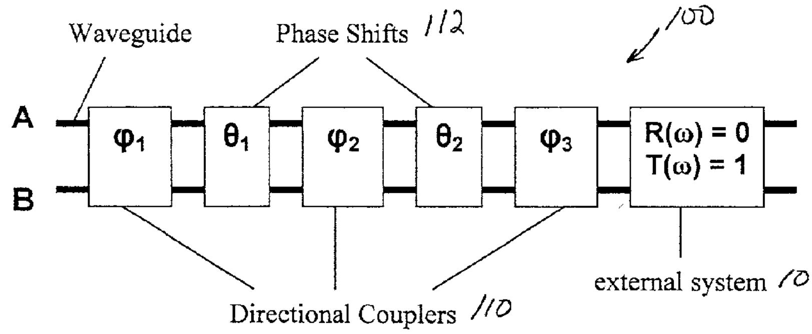

Waveguide
Phase Shifts 112
100
A
B
φ_1
θ_1
φ_2
θ_2
φ_3
R(ω) = 0
T(ω) = 1
C
D
external system 10
Directional Couplers 110

FIG. 3

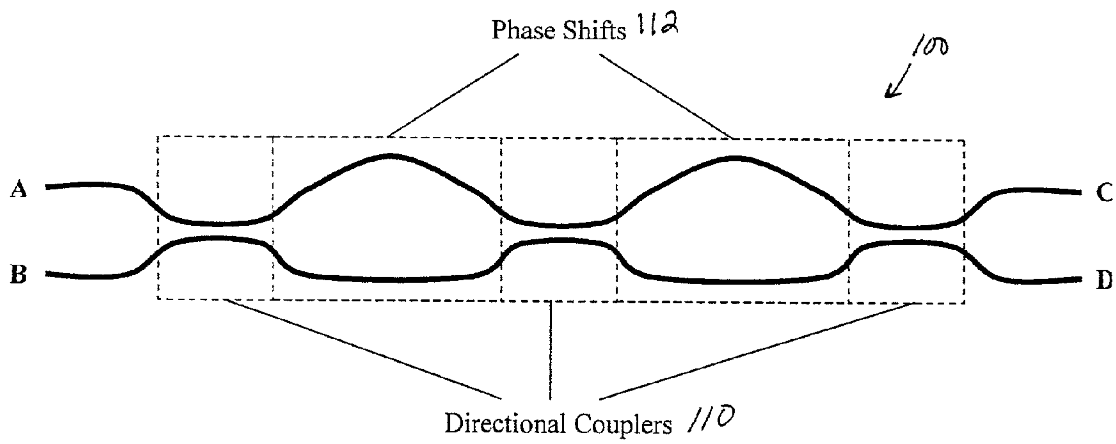

Phase Shifts 112
100
A
B
C
D
Directional Couplers 110

FIG. 4

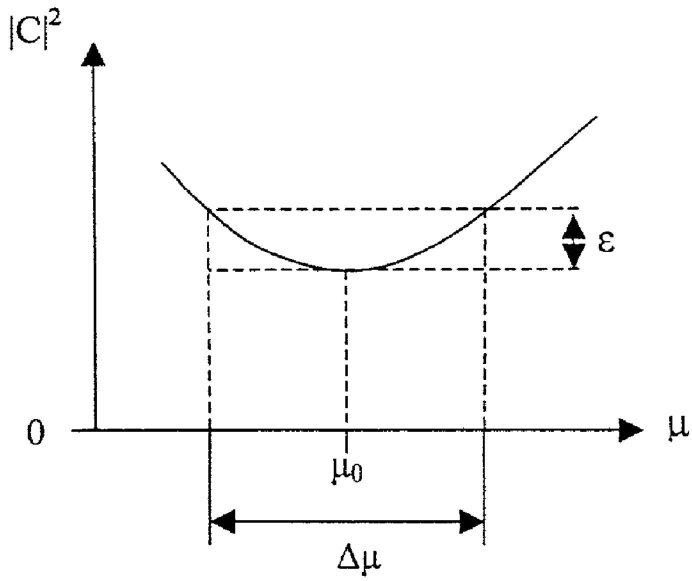

|C|²
ε
0
μ
μ0
Δμ

FIG. 5

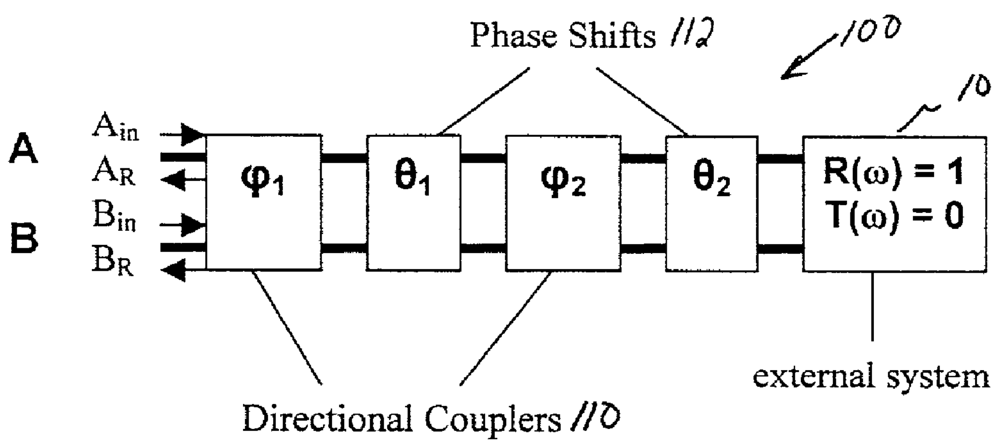

Phase Shifts 112
100
10
A
Ain
AR
B
Bin
BR
φ1
θ1
φ2
θ2
R(ω) = 1
T(ω) = 0
external system
Directional Couplers 110

FIG. 6

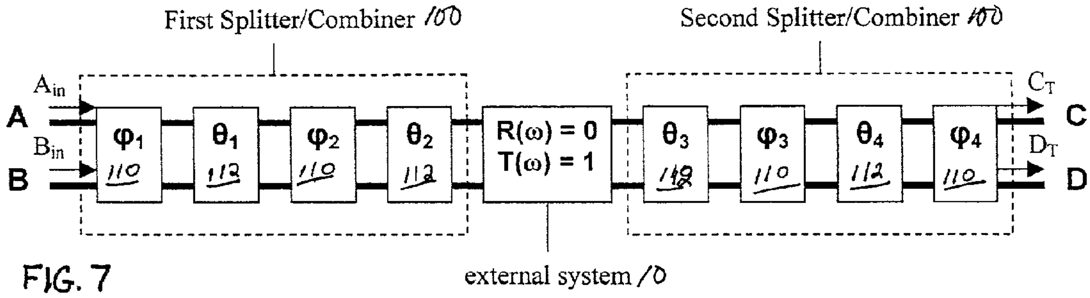

First Splitter/Combiner 100
Second Splitter/Combiner 100
A_{in}
A
B_{in}
B
φ_1
110
θ_1
112
φ_2
110
θ_2
112
R(ω) = 0
T(ω) = 1
θ_3
112
φ_3
110
θ_4
112
φ_4
110
C_T
C
D_T
D
external system 10

FIG. 7

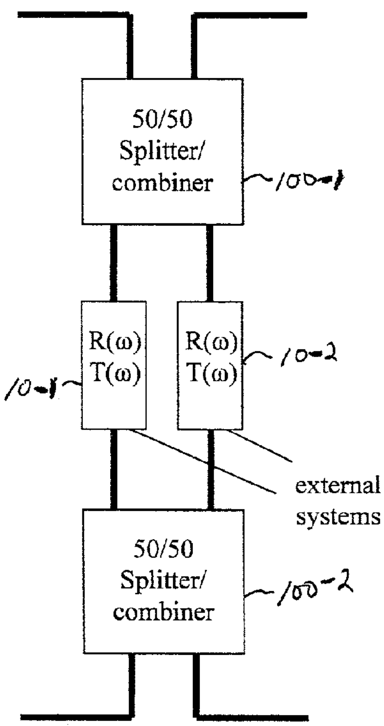

50/50
Splitter/
combiner
100-1
R(ω)
T(ω)
10-1
R(ω)
T(ω)
10-2
external
systems
50/50
Splitter/
combiner
100-2

FIG. 8

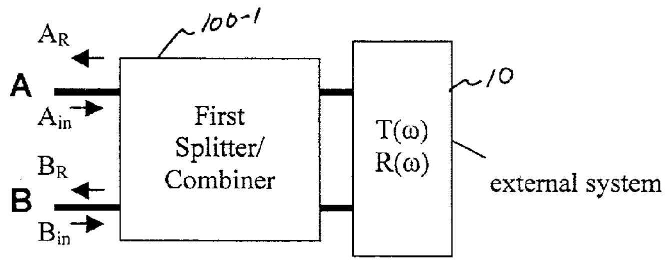


FIG. 9A

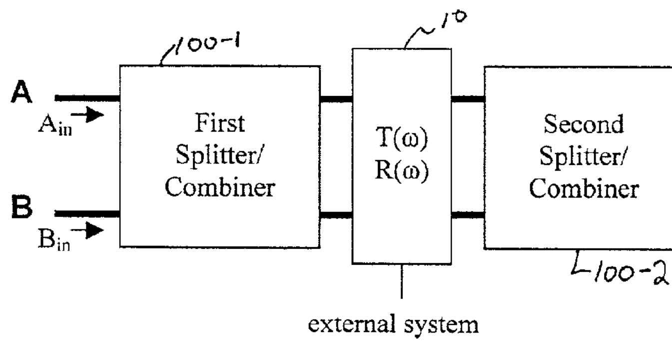


FIG. 9B

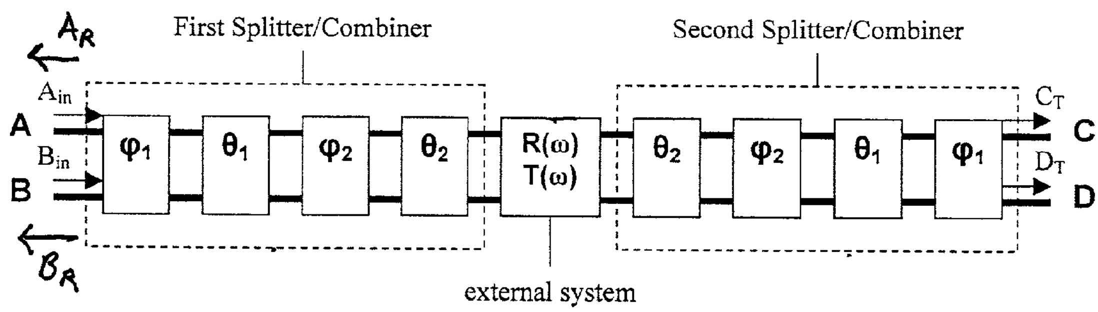
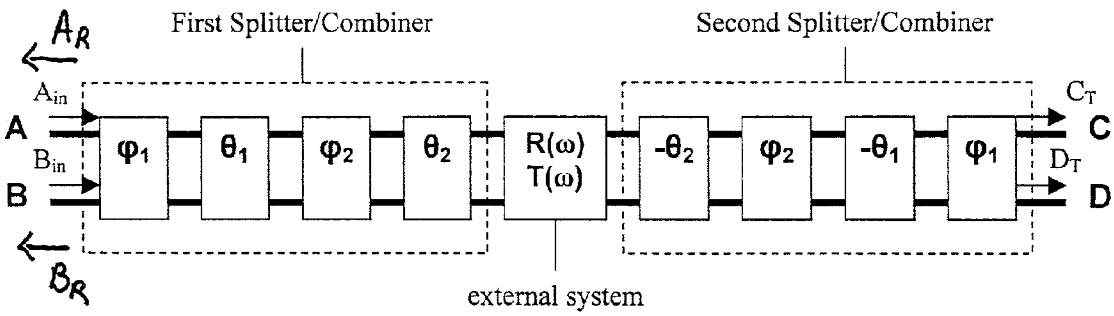


FIG. 10



A_R
First Splitter/Combiner
Second Splitter/Combiner
A_{in}
A
B_{in}
B
B_R
φ_1
θ_1
φ_2
θ_2
$R(\omega)$
$T(\omega)$
$-\theta_2$
φ_2
$-\theta_1$
φ_1
C_T
C
D_T
D
external system

FIG. 11

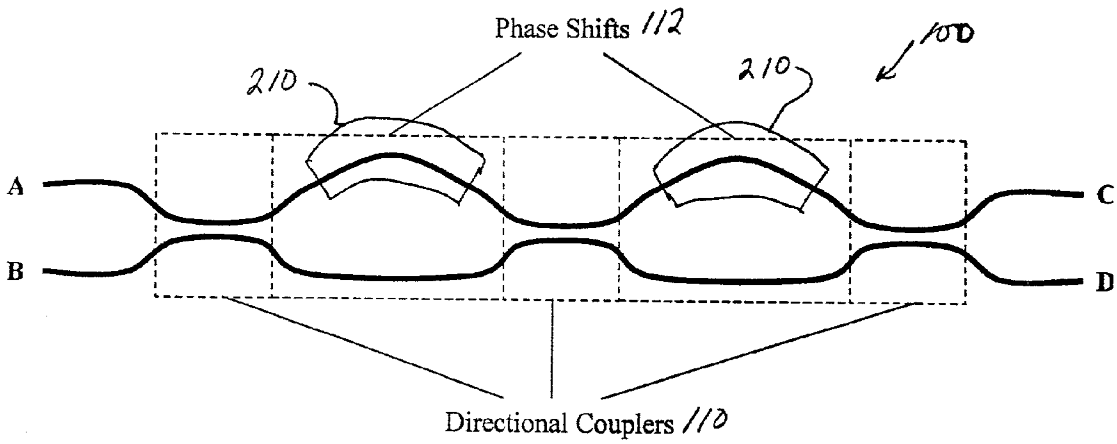


FIG. 12

POWER SPLITTER/COMBINER WITH PARAMETER TOLERANCE AND DESIGN PROCESS THEREFOR

BACKGROUND OF THE INVENTION

[0001] Power splitters/combiners are essential components in optical systems, and especially integrated, planar waveguide systems. They are important where coherent signal splitting, signal combining, or both signal splitting and combining are required. Splitters are typically used to split a single optical signal into two signals. Combiners are typically used to combine two signals into a single signal. Splitter/combiner pairs are often used to control power flow through optical elements. Splitters and combiners can also be configured as multifunctional splitter/combiners, where the operation performed depends upon the direction of the input signals and the number of inputs provided.

[0002] A frequently used splitter/combiner is composed of two waveguides that are side-coupled to each other, forming a directional coupler. Light traveling in one waveguide couples to the other waveguide so that splitting or combining can occur. For an input signal directed into a first waveguide of the directional coupler, the power splitting ratio is defined as the ratio of the percentage of power at the output of the first waveguide to the percentage of power at the output of the second waveguide. The power splitting ratio, P, is related to the coupling value, ϕ, as

$$P=\cos^2(\phi)/\sin^2(\phi) \tag{1}$$

[0003] where ϕ is the product of the coupling coefficient, μ, and the coupling length, L, of the device.

[0004] To achieve a desired power splitting ratio, the coupling value for the coupler has to be exact. For example, if the coupling value of the coupler in a 50/50 splitter is smaller than the ideal value by 10%, the power splitting ratio becomes 57.8/42.2; and if the coupling value is smaller by 20%, the power splitting ratio becomes 65.5/34.5.

[0005] The performance of directional couplers is inherently sensitive to fabrication errors. The coupling value is a function of physical parameters, such as waveguide cross-section, effective index, and waveguide-to-waveguide separation. Fabrication errors can also lead to undesired dependencies between the coupling value and the frequency and polarizations of the input optical signals, on otherwise nominally spectrally flat, polarization insensitive designs.

[0006] In order to improve performance, splitters/combiners have been proposed that include cascaded splitters and phase shifters. These systems are typically optimized for wavelength insensitivity, and sometimes robustness against uniform fabrication errors.

SUMMARY OF THE INVENTION

[0007] Previously proposed power splitter/combiner systems with phase shifts are not adequately robust against errors for many fabrication processes. This is especially true for planar waveguide fabrication in high index contrast material systems. Lithographic patterning and material deposition processes used to control waveguide cross-sections, effective indices, waveguide lengths, and waveguide-to-waveguide separations, for example, do not always provide enough control to fabricate commercially relevant systems with adequate yields.

[0008] The invention is directed to a splitter/combiner that is tolerant of parameter deviations. It is specifically applicable to integration into the transmission and/or reflection light paths of external systems. In this power splitter/combiner system, each splitter/combiner is comprised of two or more directional couplers serially connected to two or more phase shifts in an alternating order (e.g., directional coupler, phase shift, directional coupler, phase shift, directional coupler).

[0009] The invention addresses the problem of parameter deviations in splitter/combiners by selecting specific coupling and phase values for the directional couplers and phase shifts to minimize changes in an output signal in response to changes in the coupling coefficients and the propagation constants, for example. Parameter deviations, such as coupling value deviations and phase value deviations from the nominal design due to fabrication errors, for example, typically give rise to frequency dependency, polarization dependency in the output signal and are specifically addressed in the invention by designing the system so that the sensitivity of the output signal to these changes is minimized.

[0010] Additionally, the invention can be applied to address the specific problem of matched deviations in coupling values and phase values in a splitter/combiner system. The invention also addresses the problem of differential deviations in the phase values of the phase shifts by providing tunable phase shifts, employing controlled effects, such as electro-optic or thermo-optic refractive index changes.

[0011] In an exemplary embodiment of the invention, two splitter/combiners are coupled to an external system and engineered for desired reflection and transmission spectra. The splitter/combiner is designed for maximal flatness of the spectrum with respect to the deviations in the parameters in one example. Other methods, such as designing for equal-ripple of the spectrum for the desired ranges of the values for the parameters, can also be implemented. In another exemplary embodiment, two splitter/combiners are coupled to two external systems that have nominally identical reflection and transmission spectra.

[0012] The splitter/combiner system of the invention can also be designed for a wide range of ratios for splitting and/or combining signals. The invention can be used for both mono-directional or bi-directional splitting and combining.

[0013] In general, according to one aspect, the invention features a splitter/combiner system that comprises a serial connection of at least two couplers and at least two phase shifts. The coupling coefficients of the couplers and propagation constants of the phase shifts are selected to minimize changes in an output signal in response to changes in the coupling coefficients and the propagation constants.

[0014] In general, according to another aspect, the invention can be characterized as a design process for a splitter/combiner system, in which a serial connection of at least two couplers and at least two phase shifts are provisioned to connect an input waveguide to an external system. Coupling coefficients of the couplers and propagation constants of the phase shifts are proscribed to minimize changes in an output signal in response to changes in the coupling coefficients and the propagation constants.

[0015] The above and other features of the invention including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] In the accompanying drawings, reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale; emphasis has instead been placed upon illustrating the principles of the invention.

[0017] **FIG. 1** is a block diagram of a splitter/combiner coupled to an external system having a reflection and transmission spectrum, in accordance with the invention;

[0018] **FIG. 2** is a plan view of the generalized configuration of the directional couplers and phase shifts in accordance with the invention;

[0019] **FIG. 3** is a plan view of a splitter/combiner system coupled to a transmissive external optical system, according to a first embodiment of the invention;

[0020] **FIG. 4** is a plan view illustrating the layout of the waveguides in the first embodiment splitter/combiner system;

[0021] **FIG. 5** is a plot of the power of output signal C as a function of the coupling coefficient, showing a region in which changes in the coupling coefficient yields only small changes in the output signal;

[0022] **FIG. 6** is a plan view of a splitter/combiner coupled to a reflective external optical system in accordance with a second embodiment of the invention;

[0023] **FIG. 7** is a plan view of two exemplary splitter/combiners coupled an external system, in accordance with a third embodiment of the invention;

[0024] **FIG. 8** is a block diagram of a splitter/combiner system coupled to two external optical systems (sub-elements) having the same reflection and transmission spectra, in accordance with a fourth embodiment of the invention;

[0025] **FIGS. 9A and 9B** are schematic block diagrams illustrating the design process for the fourth embodiment in view of the reflection and transmission characteristics of the external system;

[0026] **FIG. 10** is a plan view of a simplified splitter/combiner configuration for reflection/transmission spectra in accordance with the invention;

[0027] **FIG. 11** is a plan view of an alternate splitter/combiner configuration for reflection and transmission spectra in accordance with the invention; and

[0028] **FIG. 12** is a plan view illustrating the layout of the waveguides in still another embodiment of the splitter/combiner system.

DETAILED DESCRIPTION OF THE INVENTION

[0029] This invention describes a splitter/combiner system that, when coupled to an external system having a reflection and/or transmission response, has a high level of tolerance to parameter deviations for the desired spectra of the output signal.

[0030] **FIG. 1** illustrates the typical application for the invention. **FIG. 1** is a block diagram of one or more of splitter/combiners **100** are coupled to an external system **10** that has reflection ($R(\omega)$) and transmission ($T(\omega)$) spectra.

[0031] The splitter/combiners **100** are monolithically fabricated from planar waveguides in a high index contrast material system in the current implementation. That is, the material system provides an index contrast between the refractive indices of the waveguides and the cladding that is greater than 1%, or preferably a higher contrast of greater than 2%. Presently, a silicon oxy-nitride system is used in which the refractive index of the waveguides is 1.60 and the refractive index of the cladding layers is about 1.44. Thus, $\Delta n/n_{cladding}$ is greater than about 10%.

[0032] The external system **10** is usually comprised of one or more devices, such as, but not limited to, waveguides, filters, and amplifiers. The splitter/combiner system can include one or more splitter/combiners **100** that are coupled to the external system **10**. As a result of increasing the tolerance of the splitter/combiner systems **100**, the performance and/or yield of the entire system is improved.

[0033] **FIG. 2** is a plan view of the generalized configuration of the directional couplers and phase shifts in accordance with the invention. **FIG. 2** shows the general design of the splitter/combiners **100** of **FIG. 1**. Each splitter/combiner **100** is preferably comprised of two or more directional couplers **110** and two or more phase shifts **112**.

[0034] Arbitrarily combining directional couplers and phase shifts in a sequential manner will generally not improve tolerance, however. Instead, the coupling value, ϕ, of each directional coupler **110** and the phase value, θ, of each phase shift **112** must be chosen carefully so that the output signals of interest have a desired power splitting ratio and a high tolerance to a particular type, or types, of parameter deviation.

[0035] Various mathematical criteria are used in designing a high parameter tolerance for the spectra of interest, such as designing for maximal flatness of the spectrum with respect to the changes in the parameters and designing for equal-ripple of the spectrum for the desired ranges of the values for the parameters. In designing for maximal flatness, the derivatives of the signal of interest with respect to the parameters of interest are engineered to be preferably negligible. In designing for equal ripple, the deviation of the spectrum of interest, from the ideal spectrum, is engineered to be within the desired tolerance for the desired parameter range. Combinations of spectra of interest, such as the reflection spectrum, the transmission spectrum, or simultaneously both the reflection and transmission spectra, can be designed for high parameter tolerance.

[0036] **FIG. 3** is a plan view of a splitter/combiner system coupled to a transmissive external optical system in accordance with a first exemplary embodiment of the invention.

The splitter/combiner system includes one splitter/combiner **100** providing a high parameter tolerance transmission spectrum at a desired power splitting ratio.

[**0037**] The exemplary splitter/combiner **100** includes three directional couplers **110** and two phase shifts **112**, which are serially connected to each other in alternating order. The splitter/combiner system is coupled to an external system **10**, which, in this embodiment, is comprised of two waveguides that have no reflection and unity transmission over the frequency range of interest, in this specific example.

[**0038**] **FIG. 4** is a plan view illustrating the layout of the waveguides in the first embodiment splitter/combiner system **100** of **FIG. 3**. Specifically, each of the directional couplers **110** comprises a region in which the waveguides AC and BD are in close physical proximity to each other. This enables the coherent combination and cross-coupling of energy between the waveguides. Each of the phase shifts **112** comprises segments of the waveguides AC and BD that have different lengths with respect to each other. This introduces a relative phase shift between signals propagating in the waveguides.

[**0039**] Using a transfer matrix method, the spectra of the splitter/combiner system are expressed as a function of parameters, such as the coupling values of the directional couplers **110** and the phase values of the phase shifts **112**. The output signals C and D for the splitter/combiner system are related to the input signals A and B as follows:

$$\begin{bmatrix} C \\ D \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}}_{\text{waveguides}} \underbrace{\begin{bmatrix} \cos(\phi_3) & -i\sin(\phi_3) \\ -i\sin(\phi_3) & \cos(\phi_3) \end{bmatrix}}_{\text{third directional coupler}} \underbrace{\begin{bmatrix} e^{i\theta_2} & 0 \\ 0 & 1 \end{bmatrix}}_{\text{second phase shift}} \underbrace{\begin{bmatrix} \cos(\phi_2) & -i\sin(\phi_2) \\ -i\sin(\phi_2) & \cos(\phi_2) \end{bmatrix}}_{\text{second directional coupler}} \underbrace{\begin{bmatrix} e^{i\theta_1} & 0 \\ 0 & 1 \end{bmatrix}}_{\text{first phase shift}} \underbrace{\begin{bmatrix} \cos(\phi_1) & -i\sin(\phi_1) \\ -i\sin(\phi_1) & \cos(\phi_1) \end{bmatrix}}_{\text{first directional coupler}} \begin{bmatrix} A \\ B \end{bmatrix} \quad (2)$$

[**0040**] where θ_1 and θ_2 are the phase values of the phase shifts and ϕ_1, ϕ_2, and ϕ_3 are the coupling values of the directional couplers. In this embodiment, an input A is preferably equally split between outputs C and D. Therefore, for an input signal A with a normalized power of 1 and an input signal B with negligible power, the outputs C and D have normalized powers of ½. The output signal C is given by,

$$C=\cos(\phi_1)\cos(\phi_2)\cos(\phi_3)e^{i\theta_1+i\theta_2}-\sin(\phi_1)\sin(\phi_2)\cos(\phi_3)e^{i\theta_2}-\cos(\phi_1)\sin(\phi_2)\sin(\phi_3)e^{i\theta_1}-\sin(\phi_1)\cos(\phi_2)\sin(\phi_3) \quad (3)$$

[**0041**] The output signal D can be described by a similar equation.

[**0042**] The splitter/combiner **100** in this embodiment has five designable parameters: 1) the coupling value of the first directional coupler, θ_1; 2) the phase value of the first phase shift, ϕ_1; 3) the coupling value of the second directional coupler, ϕ_2; 4) the phase value of the second phase shift, θ_2; and 5) the coupling value of the third directional coupler, ϕ_3. The coupling values of the directional couplers **110** are affected by the respective coupling coefficients and the coupling lengths of the directional couplers. The phase values of the phase shifts **112** are affected by the respective propagation constants and the propagation lengths of the phase shifts. Deviations in the coupling coefficients, the coupling lengths, the propagation constants, and the propagation lengths away from the nominal design will, therefore, affect the output signals C, D. Additionally, the deviations may be matched for similar devices. These effects are common to monolithic fabrication of planar waveguide systems due to the fabrication errors in layer thickness, doping to control refractive indices, and waveguide etching, for example.

[**0043**] In this first embodiment, the coupling coefficients, of the directional couplers **110** are assumed to deviate by the same amount and the propagation constants p of both phase shifts **112** deviate by the same amount, which is typical for deviations resulting from common fabrication errors that can give rise to undesired frequency dependencies and polarization dependencies.

[**0044**] According to the invention, the high tolerances for the output signals C, D are achieved by engineering the output signals C, D relative to the deviations in the coupling coefficients and the propagation constants, and specifically to matched deviations in the coupling coefficients and propagation constants, in this example.

[**0045**] In this embodiment, the coupling coefficients of the directional couplers **110** are assumed to be susceptible to a matched deviation, $\delta\mu$, and the propagation constants of the phase shifts **112** are assumed to be susceptible to a matched deviation, $\delta\beta$. To achieve a desired insensitivity to the matched deviations in this embodiment, the derivatives of the output signal C, with respect to μ and β, are preferably negligible so that the spectrum is maximally flat. The output signal C has preferably a normalized power of ½.

[**0046**] As a result of this design, the deviations of the parameter, μ, preferably do not change the normalized power of output C by greater than a desired amount, ϵ, over the desired range of the parameter, $\Delta\mu$, as shown in **FIG. 5**. **FIG. 5** is a plot of the power of output signal C as a function of the coupling coefficient, showing a region in which changes in the coupling coefficient yields only small changes in the output signal. The resulting equations are,

$$|C|^2 = \frac{1}{2} \quad (4)$$

$$\frac{\partial C}{\partial \mu} = 0 \quad (5)$$

$$\frac{\partial C}{\partial \beta} = 0 \quad (6)$$

[**0047**] Solving these equations results in the following definitions for the coupling values and the phase values in this embodiment:

$$\phi_1 = +\frac{\pi}{8} \tag{7}$$

$$\phi_2=\pi \tag{8}$$

$$\phi_3=\phi_1 \tag{9}$$

[0048]

$$\theta_1 = \cos^{-1}\left(-\frac{1}{4}\right) \tag{10}$$

$$\theta_2=-\theta_1 \tag{11}$$

[0049] The method described above can be used to obtain other exemplary embodiments of the invention. For example, the number of directional couplers and phase shifts may be extended to any desired number or other splitting ratios can be obtained.

[0050] **FIG. 6** is a plan view of a splitter/combiner **100** coupled to a reflective external optical system **10** in accordance with a second embodiment of the invention. A high parameter tolerance reflection spectrum is obtained by engineering a splitter/combiner **100** that is coupled to an external system **10** with a desired reflection spectrum in the frequency range of interest. In this embodiment, a single splitter/combiner **100** preferably contains two directional couplers **110** and two phase shifts **112**, which are serially connected to each other in alternating order.

[0051] Using the transfer matrix method, reflected output signals A_R and B_R are related to input signals A_{in} and B_{in} by the following equation,

$$\begin{bmatrix} A_R \\ B_R \end{bmatrix} = \begin{bmatrix} \cos(\phi_1) & -i\sin(\phi_1) \\ -i\sin(\phi_1) & \cos(\phi_1) \end{bmatrix} \begin{bmatrix} e^{i\theta_1} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\phi_2) & -i\sin(\phi_2) \\ -i\sin(\phi_2) & \cos(\phi_2) \end{bmatrix} \begin{bmatrix} e^{i\theta_2} & 0 \\ 0 & 1 \end{bmatrix} R(\omega) \begin{bmatrix} e^{i\theta_2} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\phi_2) & -i\sin(\phi_2) \\ -i\sin(\phi_2) & \cos(\phi_2) \end{bmatrix} \begin{bmatrix} e^{i\theta_1} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\phi_1) & -i\sin(\phi_1) \\ -i\sin(\phi_1) & \cos(\phi_1) \end{bmatrix} \begin{bmatrix} A_{in} \\ B_{in} \end{bmatrix} \tag{12}$$

[0052] In this second embodiment, the reflection spectrum, $R(\omega)$, of the external system **10** is preferably

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} r(\omega)$$

[0053] —the external system is preferably completely reflective, $r(\omega)=1$, over the frequency range of interest. The input signals, A_{in} and B_{in}, are directed in ports A and B, and the reflected output signals, A_R and B_R, are also produced at ports A and B. In this embodiment, the reflected output signal A_R is preferably negligible so that the entire input signal A_{in} is directed to reflected output signal B_R. The input signal A_{in} preferably has a normalized power of 1 and the input signal B_{in} is preferably negligible. The reflected output signal A_R is given by,

$$A_R=e^{2i\theta_2}[e^{i\theta_1}\cos(\phi_1)\cos(\phi_2)-\sin(\phi_1)\sin(\phi_2)]^2-[e^{i\theta_1}\cos(\phi_1)\sin(\phi_2)+\sin(\phi_1)\cos(\phi_2)]^2 \tag{13}$$

[0054] In this embodiment, the coupling coefficients of the directional couplers 110 are engineered for a matched deviation, $\delta\mu$, and the propagation constants of the phase shifts **112** are engineered for a matched deviation, $\delta\beta$. To achieve the desired insensitivity to the matched deviations in this embodiment, the reflected output signal A_R and the derivatives of A_R, with respect to μ and β, are preferably negligible. The resulting equations are:

$$A_R=[e^{2i\theta_2}\cos(\phi_1)\cos(\phi_2)-\sin(\phi_1)\sin(\phi_2)]^2-[e^{i\theta_1}\cos(\phi_1)\sin(\phi_2)+\sin(\phi_1)\cos(\phi_2)]^2=0 \tag{14}$$

$$\frac{dA_R}{d\mu} = 0 \tag{15}$$

$$\frac{dA_R}{d\beta} = 0. \tag{16}$$

[0055] These equations result in the following two sets of definitions for the coupling ratios and the phase shifts in this embodiment:

[0056] Set #1—

$$\phi_1 = \left(\frac{2n+1}{4}\right)\pi \tag{17}$$

$$\phi_2 = \left(\frac{2m+1}{2}\right)\pi \tag{18}$$

$$\theta_1 = 2q\pi \pm \cos^{-1}\left(-\frac{2n+1}{4m+2}\right) \tag{19}$$

-continued

$$\theta_2 = \theta_1 \tag{20}$$

[0057] where n, m are non-negative integers, $2n+1<4m+2$ and q is any integer.

[0058] Set #2—

$$\phi_1 = \left(\frac{2n+1}{4}\right)\pi \tag{21}$$

$$\phi_2 = m\pi \tag{22}$$

$$\theta_1 = 2q\pi \pm \cos^{-1}\left(-\frac{2n+1}{4m}\right) \tag{23}$$

-continued

$$\theta_2 = -\theta_1 \tag{24}$$

[0059] where n is a non-negative integer and m is a positive integer, 2n+1<4m and q is

[0060] Using Set # 1 in this exemplary embodiment, the first directional coupler is preferably a 50% coupler and the second directional coupler is preferably a 100% coupler. The first and second phase shifts are preferably both

$$+\frac{2\pi}{3} \text{ or both } -\frac{2\pi}{3}.$$

[0061] **FIG. 7** is a plan view of two exemplary splitter/combiners **100** coupled an external system **10**, in accordance with a third embodiment of the invention. The splitter/combiner system is designed for a high parameter tolerance transmission spectrum. In this embodiment, two splitter/combiners **100** are coupled to an external system **10** with a transmission spectrum. The splitter/combiners **100** in this embodiment preferably include two directional couplers **110** and two phase shifts **112** that are serially connected to each other in alternating order.

[0062] Using transfer matrix method, the output signals C_T and D_T are related to the input signals A_{in} and B_{in} by the following equation,

$$\begin{bmatrix} C_T \\ D_T \end{bmatrix} = \begin{bmatrix} \cos(\phi_4) & -i\sin(\phi_4) \\ -i\sin(\phi_4) & \cos(\phi_4) \end{bmatrix} \begin{bmatrix} e^{i\theta_4} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\phi_3) & -i\sin(\phi_3) \\ -i\sin(\phi_3) & \cos(\phi_3) \end{bmatrix} \begin{bmatrix} e^{i\theta_3} & 0 \\ 0 & 1 \end{bmatrix} \times \tag{25}$$

$$T(\omega) \begin{bmatrix} e^{i\theta_2} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(\phi_2) & -i\sin(\phi_2) \\ -i\sin(\phi_2) & \cos(\phi_2) \end{bmatrix} \begin{bmatrix} e^{i\theta_1} & 0 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \cos(\phi_1) & -i\sin(\phi_1) \\ -i\sin(\phi_1) & \cos(\phi_1) \end{bmatrix} \begin{bmatrix} A_{in} \\ B_{in} \end{bmatrix}$$

[0063] In this embodiment, the external system **10** is comprised of waveguides coupling the first splitter/combiner to the second splitter/combiner. For this embodiment, the transmission spectrum of the waveguides, T(ω), is

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} t(\omega)$$

[0064] —the waveguides are preferably completely transmissive at the frequency or frequencies of interest, so that t(ω) is preferably 1. The input is preferably directed in port A and the output is directed out ports C and D. Similar to the previous embodiment, the response of the output signal C_T is preferably negligible and the derivatives for signal C_T are preferably negligible. This embodiment can be used as a waveguide cross. In a fourth exemplary embodiment of the invention, a splitter/combiner system is designed for high parameter tolerance reflection and transmission spectra. Two splitter/combiners are coupled to an external system, such as a directional-coupler assisted add/drop filter having reflection and transmission spectra, as described, for example, in U.S. Pat. Appl. No. Unknown, entitled "Directional-coupler Assisted Add/Drop Filter With IQ Induced On/Off Switching and Modulation" filed Mar. 7, 2002 by common assignee, which is incorporated herein by reference in its entirety.

[0065] **FIG. 8** is a block diagram of a splitter/combiner system coupled to two external optical systems (sub-elements) having the same reflection and transmission spectra, in accordance with a fourth embodiment of the invention. The DCA filter resonator-system is reflective at particular frequencies and transmissive at others. The splitter/combiners **100** have 50/50 power splitting ratios and couple to the two DCA filter resonator sub-elements **10-1**, **10-2**.

[0066] **FIGS. 9A and 9B** are schematic block diagrams illustrating the design process for the fourth embodiment in view of the reflection and transmission characteristics of the external system. Splitter/combiners **100** are preferably designed separately for the reflection and the transmission spectra. Specifically, the first splitter/combiner **100-1** is designed using the parameter tolerance requirements for the reflection spectrum, similar to the second embodiment, as illustrated in **FIG. 9A**. Once the first splitter/combiner **100-1** is designed based on the reflection spectrum, the second splitter/combiner **100-2** is designed to satisfy the parameter tolerance requirements on the transmission spectrum as illustrated in **FIG. 9B**.

[0067] In this embodiment, the desired values of output signal C_T and output signal A_R are simultaneously negligible, so that there is no crosstalk and no leakage. To achieve high tolerance to common deviations in the coupling coefficients and the propagation constants, the derivatives of signal C_T and signal A_R with respect to these parameters are preferably negligible. These requirements result in definitions for the coupling values and phase values.

[0068] **FIG. 10** is a plan view of a simplified splitter/combiner configuration for reflection/transmission spectra in accordance with the invention. The design is made for a splitter/combiner for reflection and then the design is mirrored for transmission. For example, the splitter/combiner described in the second embodiment, for reflection, can also be used for transmission, as shown in **FIG. 10**. In this embodiment, the output signal A_R and output signal C_T are preferably negligible. The input signal A_{in} preferably has a normalized power of 1. The input signal B_{in} preferably has negligible power. The reflection signal A_R is:

$$A_R=\{e^{2i\theta_2}[e^{i\theta_1}\cos(\phi_1)\cos(\phi_2)-\sin(\phi_1)\sin(\phi_2)]^2-[e^{i\theta_1}\cos(\phi_1)\sin(\phi_2)+\sin(\phi_1)\cos(\phi_2)]^2\}r(\omega)=0 \tag{26}$$

[0069] and the transmission signal C_T is:

$$C_T=\{e^{2i\theta_2}[e^{i\theta_1}\cos(\phi_1)\cos(\phi_2)-\sin(\phi_1)\sin(\phi_2)]^2-[e^{i\theta_1}\cos(\phi_1)\sin(\phi_2)+\sin(\phi_1)\cos(\phi_2)]^2\}t(\omega)=0 \quad (27)$$

[0070] Since the two signals have the same form, it is clear that a solution to one equation is also a solution to the other equation. A further alternate embodiment using this method is shown in **FIG. 11**. **FIG. 11** is a plan view of an alternate splitter/combiner configuration for reflection and transmission spectra in accordance with the invention.

[0071] In another exemplary embodiment of the invention, the phase values of the phase shifts in the splitter/combiner systems are controlled by an effect, such as electro-optic or thermo-optic refractive index changes. Specifically, even with the foregoing parameter tolerant designs, in high index contrast planar waveguide systems, yields may not be high enough. This embodiment enables the phase values to vary by different amounts, addressing a differential error, for example. The differential error is corrected by tuning the phase values using a refractive effect, typically in a post-fabrication tuning step. The tolerance of the phase value, and the splitter/combiner, is thereby increased.

[0072] **FIG. 12** shows one such implementation. **FIG. 12** is a plan view illustrating the layout of the waveguides in still another embodiment of the splitter/combiner system. A post fabrication tuning mechanism is provided. Specifically, heaters **210** are integrated with the waveguides, and specifically on the phase shifts to enable post fabrication control over the refractive indices of waveguide A. This allows tuning of the propagation constants of the phase shifts **112**.

[0073] In the typical application, the operation of the splitter/combiner **100** is tested post fabrication. In the calibration sequence, the refractive indices of the waveguides are temperature tuned to optimize the splitter/combiner's performance. During normal operation, the heaters **210** maintain the waveguides at these calibrated temperatures in a steady state. Other techniques are used to fine-tune the operation of the splitter/combiner **100** in other implementations. For example, instead of temperature tuning the refractive indices, ultraviolet exposure is used to modify the waveguides in a post fabrication calibration operation.

[0074] It should be appreciated that this post fabrication fine-tuning technique is applicable to any of the previously described embodiments to improve performance of the final system.

[0075] Further, in all of the above-described embodiments, the splitter/combiner systems can be used for signal propagation in either direction. As well, each port can be used as an input port, an output port, or both an input and an output port.

[0076] The methods described above may be extended to any number of directional couplers and phase shifts. The methods may also be extended to any desired power splitting ratio and a wide range of parameter deviations. As well, the designs are not limited to any specific tolerance values or any specific set of parameters.

[0077] Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope of the invention.

What is claimed is:

1. A splitter/combiner system comprising:

a serial connection of at least two couplers and at least two phase shifts in which coupling coefficients of the couplers and propagation constants of the phase shifts are selected to minimize changes in an output signal in response to changes in the coupling coefficients and the propagation constants.

2. A splitter/combiner system of claim 1, wherein the coupling coefficients of the couplers and the propagation constants of the phase shifts are selected to minimize changes in a spectral flatness of the output signal in response to changes in the coupling coefficients and the propagation constants.

3. A splitter/combiner system of claim 1, wherein the coupling coefficients of the couplers and the propagation constants of the phase shifts are selected to minimize changes in a ripple of the output signal in response to changes in the coupling coefficients and the propagation constants.

4. A splitter/combiner system of claim 1, wherein the serial connection of at least two couplers and at least two phase shifts is fabricated in a planar waveguide system.

5. A splitter/combiner system of claim 4, wherein a contrast between an index of refraction of waveguides of the planar waveguide system relative to a cladding of the waveguides is greater than 1%.

6. A splitter/combiner system of claim 1, wherein the propagation constant of the phase shift is tunable.

7. A splitter/combiner system of claim 1, wherein the propagation constant of the phase shift is thermo-optically tunable.

8. A splitter/combiner system of claim 1, wherein a modification to the propagation constants of the phase shifts is determined in a post fabrication calibration step, which is thereafter used to control waveguide heaters.

9. A splitter/combiner system of claim 1, wherein the output signal is split between two output waveguides.

10. A splitter/combiner system of claim 9 further comprising three phase shifts that are serially connected with the two couplers in an alternating fashion.

11. A splitter/combiner system of claim 1 further comprising an external system that is reflective in a frequency range of interest.

12. A splitter/combiner system of claim 11 including two phase shifts that are serially connected with the two couplers in an alternating fashion.

13. A splitter/combiner system of claim 11, where in an input signal is received at a first waveguide of a first one of the combiners and the output signal is provided at a second waveguide of the first combiner.

14. A splitter/combiner system of claim 1 further comprising a second serial connection of at least two couplers and at least two phase shifts, which is coupled to the external system.

15. A splitter/combiner system of claim 14, wherein the output signal is provided at the second serial connection.

16. A splitter/combiner system of claim 15, wherein the output signal is provided substantially on one waveguide from the second serial connection.

17. A splitter/combiner system of claim 1 further comprising an external system that is reflective and transmissive in a frequency range of interest.

18. A splitter/combiner system of claim 17, wherein the input signal is received at a first waveguide of a first one of the combiners and the output signal is provided at a second waveguide of the first combiner.

19. A splitter/combiner system of claim 17, wherein the external system comprises a resonator system.

20. A splitter/combiner system of claim 17 further comprising a second serial connection of at least two couplers and at least two phase shifts, which is connected to the external system.

21. A splitter/combiner system of claim 17, wherein the external system comprises two resonator sub-elements with the input signal being split between the sub-elements by the serial connection.

22. A design process for a splitter/combiner system comprising:

providing a serial connection of at least two couplers and at least two phase shifts to couple an input waveguide to an external system; and

proscribing coupling coefficients of the couplers and propagation constants of the phase shifts to minimize changes in an output signal in response to changes in the coupling coefficients and the propagation constants.

23. A design process as claimed in claim 22, wherein the step of proscribing the coupling coefficients of the couplers and the propagation constants of the phase shifts comprises minimizing changes in a spectral flatness of the output signal in response to changes in the coupling coefficients and the propagation constants.

24. A design process as claimed in claim 22, wherein the step of proscribing the coupling coefficients of the couplers and the propagation constants of the phase shifts comprises minimizing changes in a ripple of the output signal in response to changes in the coupling coefficients and the propagation constants.

25. A design process as claimed in claim 22 further comprising designing the serial connection of at least two couplers and at least two phase shifts for a planar waveguide system.

26. A splitter/combiner system of claim 22, wherein a contrast between indices of refraction for waveguides of the planar waveguide system relative to a cladding of the waveguides is greater than 1%.

27. A design process as claimed in claim 22 further comprising configuring the serial connection to split the output signal between two output waveguides.

28. A design process as claimed in claim 22 further comprising providing three phase shifts that are serially connected with the two couplers in an alternating fashion.

29. A design process as claimed in claim 22, wherein the external system is reflective in a frequency range of interest.

30. A design process as claimed in claim 29 further comprising providing an input signal at a first waveguide of a first one of the combiners and the output signal is provided at a second waveguide of the first combiner.

31. A design process as claimed in claim 22 further comprising providing a second serial connection of at least two couplers and at least two phase shifts, which is connected to the external system.

32. A design process as claimed in claim 31 further comprising providing the output signal from the second serial connection.

33. A design process as claimed in claim 32 further comprising providing the output signal substantially on one waveguide from the second serial connection.

34. A design process as claimed in claim 22, wherein the external system is reflective and transmissive in a frequency range of interest.

35. A design process as claimed in claim 34 further comprising receiving the input signal at a first waveguide of a first one of the combiners and the output signal is provided at a second waveguide of the first combiner.

36. A design process as claimed in claim 34, wherein the external system comprises a resonator system.

37. A design process as claimed in claim 34 further comprising providing a second serial connection of at least two couplers and at least two phase shifts, which is connected to the external system.

38. A design process as claimed in claim 34, wherein the external system comprises two resonator sub-elements with the input signal being split between the sub-elements by the serial connection.

* * * * *