

METHOD AND APPARATUS FOR A SUBSTANTIALLY WAVELENGTH INSENSITIVE HYBRID DEVICE

FIELD OF THE INVENTION

5 The present invention relates to devices for processing electromagnetic signals and, more specifically, to hybrid electromagnetic processing devices.

BACKGROUND OF THE INVENTION

Optical processing and coupling devices such as hybrid optical couplers
10 are known in the art. Such components utilize elements of carefully chosen physical dimensions to perform power division, combination and other functions. These types of devices are typically constructed to operate at specific optical frequencies.

15 SUMMARY

Various embodiments provide an optical device that include a free space optical region and input and output optical waveguides end connecting thereto. At least one of the optical waveguides has lateral offset between two segments thereof. The lateral offset is located near the free space optical region.

20 Some deficiencies of the prior art are addressed by some embodiments of the optical device for a substantially wavelength insensitive hybrid optical device. Specifically, in such embodiments, the lateral offset produces lateral mode oscillation such that a wavelength dependency of the device is reduced with respect to a device without said offset.

25 One embodiment features an apparatus. The apparatus includes a planar integrated optical device. The planar integrated optical device has at least one input optical waveguide, a free space optical region and a plurality of output optical waveguides. The optical waveguides end connecting to the free space optical region. The at least one input optical waveguide has an offset in a core

thereof at joined ends of an input portion and an output portion of the at least one input optical waveguide.

5 BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present embodiments can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 depicts an example of a hybrid optical device known in the art;

10 FIG. 2 depicts a 90 degree substantially wavelength insensitive 2x4 hybrid optical device performing functions according to various embodiments;

FIG. 3 graphically depicts a mode oscillation profile according to various embodiments; and

To facilitate understanding, identical reference numerals have been used,
15 where possible, to designate identical elements or elements with similar function in the figures.

DETAILED DESCRIPTION

Various embodiments will be illustrated within the context of optical
20 coupling/processing functions being performed within a dual input, quad output (2x4) 90 degree hybrid planar optical device. Other embodiments may have a different number of optical inputs, e.g., more than 2, and a different number of optical outputs. Broadly speaking, the wavelength dependence of such an optical device, e.g., a star coupler, may be reduced by constructing the input
25 optical waveguides with relatively abrupt offsets or displacements that cause the field to oscillate in the optical waveguide, which oscillation will be discussed herein. The period of oscillation will change with wavelength. By controlling the design parameters according to some embodiments discussed herein, the movement of the fields may be adapted to substantially reduce the wavelength
30 dependence of the star coupler.

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FIG. 1 depicts an example of a planar optical device known in the art; namely, a star coupler 100. Star coupler 100 is a 2x4 planar optical coupler that acts as an optical 90 degree planar optical device for redistributing (e.g., splitting and/or combining) light. An optical 90 degree hybrid is a passive device. The first and second input ports receive signals A and B, respectively. The first, second, third, and fourth output ports transmit signals which are interferences between A and B with four different relative phases: 0, 90, 180, and 270 degrees, respectively. In other words, the output amplitudes from the first, second, third, and fourth output ports can be represented by $(A+B)/2$, $(A+iB)/2$, $(A-B)/2$, and $(A-iB)/2$, respectively, where i is the imaginary number. The operation of examples of conventional planar star couplers is explained, e.g., in I. Kaminow / T. Li, *Optical Fiber Telecommunications IVI Components*, Chapter 9 sections 2.4 – 2.6 by Chris Doerr, copyright 2002, Elsevier Science, ISBN: 0-12-395172-0, which is incorporated herein by reference in its entirety.

Star coupler 100 includes input waveguides 110₁₋₂, a free space region 120, and output waveguides 130₁₋₄. Star coupler 100 also may include optional unused dummy waveguides 140 to help make optical coupling and fabrication of star coupler 100 more uniform around the input and output waveguides 110₁₋₂ and 130₁₋₄. When star coupler 100 is acting as an optical power splitter, electromagnetic (EM) waves (i.e., optical signals) of a given intensity enter the coupler 100 through input waveguides 110₁₋₂, disperse through free space region 120 and are dividedly output through output waveguides 130₁₋₄.

A 90-degree optical hybrid in existing planar optical devices such as star coupler 100 is formed by a construction that suitably provides for differences in the optical path lengths over the different optical paths within the coupler through which EM waves propagate between inputs and outputs of the device. The optical path-length differences produce differing relative phases between light waves arriving at (and propagating through) respective output waveguides of the device. These phase differences ($\Delta\phi$) are a function of a precise design wavelength value (λ_d) based on the physical dimensions of the hybrid device.

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For a 2x4 star coupler such as coupler 100, $\Delta\phi$ from waveguide m1 to waveguide m2 is expressed by the following equation:

$$\Delta\phi = \frac{\pi}{2} \left(m_1 - \frac{5}{2} \right) \left(m_2 - \frac{5}{2} \right) \frac{\lambda_d}{\lambda} \quad (1)$$

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wherein λ is the wavelength of an EM wave passing through the device, m_1 may equal integer values 2 or 3 (because the central two waveguides of the four possible waveguides are used on the input side of the 90-degree hybrid), and m_2 may equal integer values 1, 2, 3 or 4. Specifically, $m_1 = 2$ for waveguide 110₁,
 10 $m_1 = 3$ for waveguide 110₂. $m_2 = 1, 2, 3$, and 4 for waveguides 130₁, 130₂, 130₃, and 130₄, respectively. Thus, the operational characteristics of such existing hybrid devices are wavelength dependent, which may preclude their use in some wideband optical applications.

FIG. 2 depicts a 90-degree, substantially wavelength-insensitive 2x4
 15 hybrid optical device that functions according to some embodiments. Specifically, the substantially wavelength insensitive 2x4 planar optical coupler 200 comprises a 2x4 planar optical coupler including input waveguides 210₁₋₂, a free space region 220, output waveguides 230₁₋₄ and optional dummy waveguides 140. However, unlike conventional star coupler 100 of FIG. 1, each
 20 input portions of the input waveguides 210₁₋₂ of coupler 200 has input portions 212₁₋₂ and output portions 214₁₋₂, which are end-connected and are positioned to have a relative lateral offset 240 therebetween. In particular, the axis of the input portion 212₁₋₂ of each input waveguide 210₁₋₂ is laterally offset with respect to the axis of an output portion 214₁₋₂ of the same input waveguide input 210₁₋₂. For
 25 example, the sidewalls of the input portions 212₁₋₂ and output portions 214₁₋₂ of the input waveguides 210₁₋₂ have abrupt relative offsets at the joined ends.

Each input portion 212₁₋₂ is, e.g., relatively displaced towards the center symmetry line of coupler 200 with respect to the output portion 214₁₋₂ of the same input waveguide 210₁₋₂. However, it is also contemplated that in other

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embodiments, the offset may be oriented away from the coupler 200. The offset 240 operates to produce lateral movement of modes within input waveguides 210₁₋₂, causing oscillation of the modes in the guide and providing some degree of wavelength insensitivity of the device according to some embodiments, which will be explained below. The oscillation is transverse with respect to the length of the waveguide, referring to propagating waves moving in a “zig-zag” pattern longitudinally along the guide and leaving the guide at different positions with respect to the center of the guide. The specific meaning of “oscillation” herein will be explained in more detail with respect to FIGs. 3A-3C. However, a more detailed discussion of the dimensions of an exemplary coupler 200 (e.g., the values l , R , w_{eff} , θ_1 and θ_2) will first be provided below.

Referring to the embodiment in FIG. 2, each offset 240 between an input portion 212₁₋₂ and an output portion 214₁₋₂ of the same input optical waveguide 210₁₋₂ is constructed to be non-adiabatic. That is, each input portion 212₁₋₂ of the input optical waveguide 210₁₋₂ is abruptly laterally shifted with respect the output portion 214₁₋₂ of the same optical waveguide 210₁₋₂ at the connecting region. Each respective input portion 212₁₋₂ and output portion 214₁₋₂ of input waveguides 210₁₋₂ is also wide enough to support multi-mode optical propagation therein.

The propagation constant β of a mode ν in a multi-mode waveguide is expressed by the following equation:

$$\beta_\nu \approx kn_f - \frac{\pi^2(\nu+1)^2}{2kn_fw_{eff}^2} \quad (2)$$

where k is the propagation constant in free (i.e., $k = 2\pi/\lambda$), n_f is the core refractive index and w_{eff} is the effective width of the waveguide, oriented in the direction of polarization.

Various specific embodiments to be discussed and the equations that follow refer to waveguides supporting up to approximately 5 modes. However,

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other embodiments are also envisioned that utilize waveguides supporting a greater number of modes while still adhering to the general principles of embodiments described herein. When multi-mode wave propagation is supported in one of the input waveguides 210₁₋₂, lateral mode oscillation is
 5 facilitated by constructing the offset 240 between the input portion 212₁₋₂ and output portion 214₁₋₂ of the same input waveguides 210₁₋₂ has an approximate beat length L_b expressed as:

$$L_b \approx \frac{4kn_f w_{eff}^2}{\pi} \quad (3a)$$

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where $k = 2\pi / \lambda$. As such, approximation (3a) may also be expressed as:

$$L_b \approx \frac{8n_f w_{eff}^2}{\lambda} \quad (3b)$$

In both of equations (3a) and (3b), T_{osc} depends on λ . The inventor
 15 believes that if the number of excited modes is less than or equal to approximately 5, then there is an approximate beat length which is 3 times shorter than this. For simplicity in explanation, it will be assumed that the number of modes is less than or equal to approximately 5. Thus the following equation will be used:

$$20 \quad L_b \approx \frac{8n_f w_{eff}^2}{3\lambda} \quad (3c)$$

wherein n_f = the core refractive index of the at least one or the one or more input optical waveguides; w_{eff} = the effective width of the respective input waveguide; and λ = a standard telecom wavelength, such as the C-band telecom
 25 wavelength of 1,550 nm. It is noted that as a practical matter, L_B is in one embodiment approximated to +/- 0.1 L_B .

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It is preferable to operate at the steepest point in the beat cycle. Thus it is desirable to have the length of the multimode waveguide to equal approximately $1/4 + A/2$ times the beat length, where A is any integer greater than or equal to zero. Thus the output portion 214₁₋₂ of the input waveguides 210₁₋₂, of coupler 200 have a length l as depicted in FIG. 2 that is expressed by the following equation:

$$l = \frac{2(1+2A)n_f w_{eff}^2}{3\lambda_d} \quad (4)$$

The input and output boundaries of the free space region of the coupler 200 have a radius of curvature R . The dimensions of coupler 200 include angles θ_1 and θ_2 . θ_1 is the angle between the position (e.g., center of energy) of the center of the wavefront of a light wave at the input boundary 222 as the light wavefront exits input waveguide 210₁ according to various embodiments, and the intersection 252 of output waveguides 230₂ and 230₃ at the output boundary 222 of free space region 220 at the opposite side of the coupler 200, with respect to a vertical centerline 250. θ_2 is the angle between the intersection 254 of input waveguides 210₁ and 210₂ at the input boundary 222 of free space region 220 and the center of output waveguide 230₄ with respect the centerline 250 at the output boundary 222. By choosing the appropriate values of l and w_{eff} (e.g., according to equation 4), mode oscillation is facilitated.

An illustration of optical mode oscillation will now be discussed. As has already been described with respect to equation (3b), L_b depends on wavelength λ . In one embodiment, λ_d is a standard telecom wavelength, such as the C-band telecom wavelength of 1,550 nm. In the referenced embodiment involving planar optical coupler 200, the phase difference from a port at θ_1 to another port at θ_2 - i.e., ϕ_{12} - is expressed by the following equation:

$$\phi_{12} = kR\theta_1\theta_2 = \frac{2\pi}{\lambda}R\theta_1\theta_2 \quad (5)$$

From Eq. (5), one can see that ϕ_{12} depends on λ , which gives rise to the
 5 unwanted wavelength dependence of the coupler. Since waveguide 210₁ is wide
 enough to support multi-mode propagation, it will be shown that the relative
 lateral position of the center of the propagating optical mode in the optical
 waveguide changes the value of θ_1 when λ changes. This movement of θ_1 can
 be designed to partially or mostly cancel the net dependence of ϕ_{12} on λ , thus
 10 substantially reducing or eliminating wavelength dependency of the coupler.

In various embodiments of coupler 200, the size of the lateral offsets 240
 between the input portions 212₁₋₂ and the output portions 214₁₋₂ of the same
 input waveguides 210₁₋₂ may vary. Generally speaking, the larger the lateral
 offset 240, the larger the transmission loss that will occur to an incident wave
 15 thereto. Too large an offset will produce too large a loss, while too small an
 offset will lead to a lack of sufficient lateral oscillation of the optical mode in the
 waveguide to significantly reduce the wavelength dependency of the optical
 coupler 200. Typical offsets 240 that have been utilized by the inventor include
 $w_{eff}/4$. That is offset input portions of the input portions 212₁ and 212₂ of the
 20 input waveguides are set inward (toward the centerline of coupler 200) by a
 length of $w_{eff}/4$ with respect to the output portions 214₁ and 214₂ of the input
 waveguides. But, embodiments are also envisioned where one are more offsets
 are set outward with respect to the centerline of coupler 200. In various
 embodiments, for instance, If the value 'A' in equation (4) is an even integer, the
 25 offsets 240 of input portions 212₁₋₂ are positioned inward toward the centerline
 250 of coupler 200. Conversely If 'A' is an even integer, the offsets 240 of input
 portions 212₁₋₂ are positioned outward away the centerline 250 of coupler 200.
 The position of the center of the propagating optical modelateral to the direction
 of propagation in the multi-mode waveguide at the star coupler free-space region

boundary will change with λ . This movement of the lateral center of a propagating mode can compensate for the wavelength-dependence in the relative phase difference between light received at the ends of adjacent output waveguides, i.e., at the second or output boundary 222 of the star coupler 220.

5 In one embodiment, the offset has a size of about $w_{eff}/4 \pm (0.1)w_{eff}/4$, wherein $w_{eff}/4$ is a width of a core of the at least one of the one or more input optical waveguides.

Generally speaking, offsets of $w_{eff}/2$ or less, when utilized in embodiments such as coupler 200, can keep the offsets substantially non-adiabatic and
10 produce the desired oscillatory effects. It should be emphasized however, that any specific mention of a particular offset 240 value (e.g., $w_{eff}/2$ and/or $w_{eff}/4$) herein is provided purely as an example, and should not be construed as limiting the scope of any referenced or other embodiments to any particular dimensional constraint(s). Rather, any suitable offset value or other means of producing
15 oscillation may be utilized while still adhering to the overall principles.

It is important to note that teachings herein are broadly applicable to facilitating substantial wavelength independence of relative phases in adjacent output waveguides in planar optical devices. The embodiments adapt or cause various modes of optical or electrical oscillations in input and/or output
20 waveguides of the device. Thus, an oscillation caused by an offset 240 in waveguides 210₁₋₂ is merely an example pertaining to one particular embodiment.

FIGs. 3A-3C depict exemplary oscillation profiles 310, 320 and 330 of optical propagating modes, useful in understanding various embodiments such
25 as the one described with respect to the embodiment of FIG. 2. Mode oscillation profiles 310, 320 and 330 of the optical propagating mode are shown for illustrative purposes as occurring in waveguide 210 (of coupler 200), with offset 240 and offset and non-offset waveguide portions 212 and 214 respectively.

Mode oscillation profiles 310, 320 and 330 are not drawn to any particular scale
30 or with respect to any specific wavelengths, but are intended to be viewed in

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comparison to each other to illustrate the concept of how beat length changes with λ relative to λ_d in waveguide structures such as waveguides 210₁₋₂.

Mode oscillation profile 310 depicts the path of the center energy of one or more modes laterally oscillating (due to offset 240) in a “zig-zag” pattern while
5 propagating longitudinally along a non-offset waveguide portion 214 of a waveguide 210, to produce reduced wavelength sensitivity of the device (e.g., coupler 200) to which the waveguide is connected, according to various embodiments. The period of oscillation (T_{osc}) corresponds to beat length as defined by equations (3a) and (3b). Beat length L_b of mode oscillation profile 310
10 is indicative of $\lambda = \lambda_d$. By contrast, mode oscillation profile 320 depicts an example of beat length (relative to mode oscillation profile 310) when $\lambda < \lambda_d$. In following with equations (3a) and (3b), the beat length L_b of mode oscillation profile 320 is thus increased compared to the $\lambda = \lambda_d$ beat length example of mode oscillation pattern 310. Finally, oscillating mode profile 330 illustrates an
15 exemplary beat length according to $\lambda > \lambda_d$, which is decreased relative to oscillation profile 310.

The mode oscillation profiles discussed with respect to FIGs. 3A-3D may be adapted to influence response characteristics of devices according to various embodiments, such that wavelengths to which such devices are less sensitive to
20 pass through the devices with little or no encumbrance, while wavelengths to which the device is more sensitive to are reduced or attenuated. Various embodiments impart mode oscillations using different structures and techniques, such as described herein in more detail. Generally speaking, the mode oscillations are implemented in a manner adapted to the specific wavelength
25 sensitivities of the device. The various equations discussed herein may be used to calculate the appropriate mode oscillation profile. Alternatively, the mode oscillation profile may be determined empirically.

FIG. 3D depicts a coupler 340, similar to coupler 200, illustrating further details of how mode oscillation may be facilitated in the connection terminals of

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devices utilizing offsets such as offset 240 of FIG. 2, to produce mode oscillation in the terminals (e.g., waveguides) and decrease wavelength sensitivity according to various embodiments. Like coupler 200, coupler 340 is a 90 degree, substantially wavelength insensitive 2x4 hybrid optical device, including

5 input waveguides 210₁₋₂, a free space region 220, output waveguides 230₁₋₄, dummy waveguides 140, offsets 240 and respective offset portions 212₁₋₂ and non-offset portions 214₁₋₂. As mentioned with respect to the exemplary embodiment depicted in FIG. 2 and equation (5), a change in excitation wavelength λ in the coupler 200 (and coupler 340) creates a shift of θ_1 ,

10 providing wavelength insensitivity of the coupler(s) according to various embodiments.

The dynamic shifting capability of θ_1 , which was previously discussed with respect to FIGs. 3A-3C is displayed as θ_1 shift range 345 in FIG. 3B. If excitation wavelength λ is equal to the design wavelength λ_d ($\lambda = \lambda_d$), the lateral

15 orientation of optical energy as it exits waveguide 210 is in the center of the guide, and θ_1 remains same value as it would be if there were no offset 240. When the coupler (200 or 340) excitation wavelength λ is greater than the design wavelength λ_d , as is shown in mode oscillation profile 330 of FIG. 3C, beat length L_b is reduced (e.g., according to equation (3b)), causing the lateral

20 orientation of optical energy exiting the waveguide 210 to be situated farther away from the horizontal centerline 250 of the coupler compared to its position if $\lambda = \lambda_d$ making θ_1 larger. Conversely, when excitation wavelength λ is less than the design wavelength λ_d , such as in oscillation profile 320 of FIG. 3C, beat length is increased, causing the lateral orientation of optical energy in the

25 waveguide 210 to be situated closer to the horizontal centerline 250 of the coupler (compared to the $\lambda = \lambda_d$ case), making θ_1 smaller.

Various embodiments impart mode oscillations using different structures and techniques, such as described herein in more detail. Generally speaking, the mode oscillations are implemented in a manner adapted to the specific

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wavelength sensitivities of the device. The various equations discussed herein may be used to calculate the appropriate mode oscillation profile. Alternatively, the appropriate mode oscillation profile may be determined empirically.

FIGs. 2 and 3A-3D depict offsets 240 on the outer side of input waveguides 210₁₋₂. That is, non-offset output portion 214 as an end positioned at the input boundary 222, between free space region 220 and offset portion 212. In various embodiments, if the length l in FIG. 2 is less than half the beat length L_b (e.g., per equations 3a and/or 2b) will provide a lateral movement of the guided mode that will partially compensate wavelength dependence of the relative phase at the ends of adjacent output waveguides 230₁ and 230₂. In other embodiments, if l is larger than T_{osc} then the relative lateral offset positions of input portions 212 of the input waveguide and the output portions 214 of the input waveguides should be reversed. Various embodiments are also envisioned wherein planar optical devices are constructed with input portions 212 and output portions 214 of the input optical waveguide are in both the preceding orientations.

Various embodiments are also envisioned where the oscillation produced in the guided optical mode is adjustable. That is, oscillation profiles such as respective oscillation profiles 310, 320 and 330 of FIGs. 3A-3C are not based solely on the device's physical dimensions and material composition. For instance, it is contemplated that in one embodiment, a planar optical device such as coupler 200 is constructed on an Indium Phosphide (InP) semiconductor substrate with electrodes positioned along the length of a multi-mode waveguide (lead), such as 214₁₋₂. By suitably biasing the electrodes, a current is created in the guide changes the refractive index along its length. By adjusting refractive index (e.g., beat length), the properties of the oscillation may be moved, and/or the coupler may be tuned.

It should be emphasized, however, that various embodiments as a whole should not be construed as being limited by any characteristic dimensions and/or construction details particular to any exemplary embodiment discussed herein.

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Likewise, although particular embodiments discussed herein are optical devices, the overall basic principles of the various embodiments as a whole are not at all limited to optical devices. It is fully envisioned that the basic principles of the various embodiments as a whole can be equally applied to electrical devices,
5 including distributed element varieties, or any other type of device wherein wavelength dependency is controlled by causing an oscillating mode in at least one lead thereof.

While the foregoing is directed to various embodiments, other and further embodiments may be devised without departing from the basic scope thereof.
10 As such, the appropriate scope is to be determined according to the claims, which follow.

What is claimed is:

1. An optical device, comprising:
a free space optical region;
- 5 one or more input optical waveguides end connected to the free space optical region along a first surface thereof; and
one or more output optical waveguides end connected to the free space optical region along a second surface thereof, the second surface facing the first surface;
- 10 wherein at least one of the one or more input optical waveguides supports multi-mode propagation and includes an offset at joined ends of an input portion and an output portion thereof, the output portion end connecting to the first surface; and
wherein the set of input and output optical waveguides includes at least
- 15 three optical waveguides.
2. The optical device of claim 1, wherein the offset is adapted to cause an oscillating mode in the at least one of the one or more input optical waveguides.
- 20 3. The optical device of claim 2, wherein the oscillating mode has a beat length L_b of approximately:

$$L_b \approx \frac{8n_f w_{eff}^2}{3\lambda}$$

wherein:

- 25 n_f = the core refractive index of the at least one or the one or more input optical waveguides;
- w_{eff} = the effective width of the respective input waveguide; and
- λ = a standard telecom wavelength.

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4. The optical device of claim 1, wherein the output portion of the at least one of the one or more input waveguides has a length l expressed as:

$$l = \frac{2(1+2A)n_f w_{eff}^2}{3\lambda_d}$$

5 wherein:

n_f = the core refractive index of the waveguide;

w_{eff} = an effective width of the at least one of the one or more input optical waveguides;

λ_d = a standard telecom wavelength; and

10 A = an integer ≥ 0 .

5. The optical device of claim 1, wherein the offset has a size of about $w_{eff}/4 \pm (0.1)w_{eff}/4$, wherein $w_{eff}/4$ is a width of a core of the at least one of the one or more input optical waveguides.

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6. The optical device of claim 6, wherein the optical device is a star coupler.

7. An apparatus comprising:

a planar integrated optical device having at least one input optical waveguide, a
20 free space optical region and a plurality of output optical waveguides, the optical waveguides end connecting to the free space optical region, wherein:

the at least one input optical waveguide includes an offset in a core thereof at joined ends of an input portion and an output portion of the at least one input optical waveguide.

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8. The apparatus of claim 7, wherein the optical device is constructed on a planar semiconductor substrate and the refractive index of a portion of the at least one input optical waveguide is adjustable via an electrical bias applied thereto.

9. A method of operating a planar integrated optical device having an input optical waveguide, a free space optical region and a plurality of output optical waveguides, comprising:

- 5 sending light into a first end of the input optical waveguide such that a center of a guiding mode of the light laterally oscillates in the input optical waveguide near and before a second end thereof, the second end connecting to a surface of the free space optical region, the output optical waveguides end connecting to the free space optical region.

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10. The method of claim 9, further comprising:

adjusting a refractive index of a portion of the input optical waveguide near the second end to cause the center of the guiding mode to laterally oscillate in the input optical waveguide near the second end.