The invention discloses a semi-ring Fabry-Perot (SRFP) optical resonator structure comprising a medium including an edge forming a reflective facet and a waveguide within the medium, the waveguide having opposing ends formed by the reflective facet. The performance of the SRFP resonator can be further enhanced by including a Mach-Zehnder interferometer in the waveguide on one side of the gain medium. The optical resonator can be employed in a variety of optical devices. Laser structures using at least one SRFP resonator are disclosed where the resonators are disposed on opposite sides of a gain medium. Other laser structures employing one or more resonators on one side of a gain region are also disclosed.

20 Claims, 32 Drawing Sheets
FIG. 1E

FIG. 1F
FIG. 2C
FIG. 5

Output Power (Watts)

Input Current (Amperes)
OPTICAL RESONATOR
CROSS-REFERENCE TO RELATED APPLICATIONS

This continuation application claims the benefit under 35 U.S.C. §120 of the following co-pending U.S. Patent Application, which is incorporated by reference herein:


STATEMENT OF GOVERNMENT RIGHTS

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 U.S.C. 202) in which the Contractor has elected to retain title.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to optical devices and methods for producing and operating them. Particularly, the present invention relates to optical resonators and their applications in tunable semiconductor lasers.

2. Description of the Related Art

In recent years, the development of optical devices for various applications such as tunable semiconductor lasers has received much attention. For example, fiber optic communication systems employ widely tunable semiconductor lasers in wavelength division multiplexing applications. Accordingly, various forms of tunable semiconductor lasers and related devices have been developed.

Many of the developed tunable semiconductor lasers require relatively complex manufacturing processes and may employ grating structures and/or moving components. In addition, multiple optical couplers in many tunable semiconductor lasers can reduce the overall performance, such as indicated by the mode suppression ratio (MSR). A filter in one simple architecture. The MSR exhibited by embodiments of the invention (even in the case of low, e.g. approx. 3 dB, coupling between the gain chip and the tunable mirror) is still higher than that obtained with standard designs of tunable lasers based on interferometer techniques. Such standard designs exhibit typical MSRs around 30 dB to 40 dB.

The novel optical resonator of the present invention, hereinafter referred to as a semi-ring Fabry-Perot (SRFP) resonator comprises a medium including an edge forming a reflective facet and a waveguide within the medium, the waveguide having opposing ends formed by the reflective facet. The performance of the optical resonator can be further enhanced by including a Mach-Zehnder interferometer in the waveguide. The SRFP exhibits its own reflection spectra having a substantially uniform peak transmission at all resonant peaks. The free spectral range of a SRFP is related to its optical length. Accordingly, tuning can be achieved by shifting the peaks by an adjustment of the index of refraction in at least a portion of the SRFP waveguide through current injection.

The SRFP can be employed in a variety of optical devices, such as a semiconductor laser where the resonator is coupled through a coupling region to a gain medium within a Fabry-Perot cavity. A typical laser embodiment of the invention comprises a gain chip including at least one tunable filter element including the novel resonator. There are different acceptable techniques for coupling the gain medium to the tunable feedback element. However, the nature of the coupling is not important for an analytical study of the device.

Some advantages of the SRFP resonator over a conventional ring resonator are that the SRFP resonator supports standing waves and a larger waveguide bending curvature can be used, reducing potential bending losses. Also, the SRFP resonator uses only one coupling region in order to couple back to the gain medium. In addition, one advantage of the SRFP over a conventional Fabry-Perot cavity resonator is the use of only one plane mirror for both reflecting

SUMMARY OF THE INVENTION

The present invention discloses a novel optical resonator that can be employed in new classes of widely tunable semiconductor lasers and other optical devices. Embodiments of the invention have the advantage of requiring only simple planar fabrication technology. Thus, embodiments of the invention require no grating structure or moving parts. Using a complex field approach, it can be demonstrated that relatively wide tunability, high optical power and a large mode suppression ratio (MSR) can be achieved through a careful design employing this simple architecture. The MSR exhibited by embodiments of the invention (even in the case of low, e.g. approx. 3 dB, coupling between the gain chip and the tunable mirror) is still higher than that obtained with standard designs of tunable lasers based on interferometer techniques. Such standard designs exhibit typical MSRs around 30 dB to 40 dB.

The novel optical resonator of the present invention, hereinafter referred to as a semi-ring Fabry-Perot (SRFP) resonator comprises a medium including an edge forming a reflective facet and a waveguide within the medium, the waveguide having opposing ends formed by the reflective facet. The performance of the optical resonator can be further enhanced by including a Mach-Zehnder interferometer in the waveguide. The SRFP exhibits its own reflection spectra having a substantially uniform peak transmission at all resonant peaks. The free spectral range of a SRFP is related to its optical length. Accordingly, tuning can be achieved by shifting the peaks by an adjustment of the index of refraction in at least a portion of the SRFP waveguide through current injection.

The SRFP can be employed in a variety of optical devices, such as a semiconductor laser where the resonator is coupled through a coupling region to a gain medium within a Fabry-Perot cavity. A typical laser embodiment of the invention comprises a gain chip including at least one tunable filter element including the novel resonator. There are different acceptable techniques for coupling the gain medium to the tunable feedback element. However, the nature of the coupling is not important for an analytical study of the device.

Some advantages of the SRFP resonator over a conventional ring resonator are that the SRFP resonator supports standing waves and a larger waveguide bending curvature can be used, reducing potential bending losses. Also, the SRFP resonator uses only one coupling region in order to couple back to the gain medium. In addition, one advantage of the SRFP over a conventional Fabry-Perot cavity resonator is the use of only one plane mirror for both reflecting
facets. This eases the fabrication of the resonator; the length of the SRFP resonator can greatly differ from that of the chip and the SRFP resonator can be tuned for optimum frequency selection. This yields the further advantage that the FSR of the SRFP resonator is not strongly dictated by fabrication requirements, as it is in the case of conventional Fabry-Perot resonators.

In one exemplary embodiment, the tunable filter element within the gain chip can be constructed by the combination of a Mach-Zehnder interferometer (MZI) within the SRFP inside a Fabry-Perot cavity. The Fabry-Perot cavity includes a waveguide comprising two opposing ends which conclude at a common high refection facet, forming the SRFP. A coupling region interrupts the waveguide and couples it to the gain medium within the device. The MZI, having a large free spectral range, is included in the waveguide on one side of the coupling region and selects a particular wavelength region within the gain bandwidth. However, this interferometer does not provide sufficient discrimination between neighboring cavity modes. See e.g., Amann, Markus-Christain et al., “Tunable Laser Diodes”, Artech House Publishers, 1998; Kuznetsov, M. et al., “Widely tunable (45 nm, 5.6 THz) multi-quantum well three-branch Y3-lasers for WDM networks”, IEEE Photonics Technology Letters, Vol. 5, 1993, pp. 879-882; and Borchert, B. et al., “Vertically integrated Mach-Zehnder interferometer (VMZ) widely tunable laser diode with improved wavelength access”, Electronics Letters, Vol. 30, 1994, pp. 2047–2049.

Therefore, the SRFP with a small free spectral range selects a particular cavity mode within the wavelength region selected by the MZI. The frequency tunability is obtained by changing the difference of optical length between the two arms of the MZI; the SRFP defines the finesse of the reflector.

In addition, in further embodiments of the invention detailed hereafter multiple resonators, and particularly SRFP resonators, are used to produce tunable lasers. Further embodiments of the invention include a novel class of tunable semiconductor lasers using the Vernier technique where the two resonators are localized in the same side of the gain medium. These devices can exhibit both high tunability through application of the Vernier technique and high power because the two resonators are localized in the same side of the gain medium.

In still further embodiments of the invention, other novel laser structures are also disclosed which do not employ the semi-ring Fabry-Perot resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

FIG. 1A illustrates a top view of an optical resonator of the invention;

FIG. 1B illustrates a top view of an optical resonator of the invention including a Mach-Zehnder interferometer;

FIG. 1C illustrates a frequency selective mirror device comprising a MZI and a mirror;

FIG. 1D qualitatively illustrates the reflection output of the frequency selective mirror device using the MZI with respect to frequency;

FIG. 1E qualitatively illustrates the reflectance of the SRFP of the present invention;

FIG. 1F qualitatively illustrates the combined response of the MZI and the SRFP resonator;

FIG. 2A illustrates a top view of a tunable laser embodiment of the present invention including a tunable element having two waveguides, a MZI and a reflective facet;

FIG. 2B illustrates a top view of a second tunable laser embodiment of the present invention including a tunable element having a ring resonator and a MZI;

FIG. 2C illustrates a top view of a structural variant of the FIG. 2B embodiment of the present invention including a tunable element having a ring resonator and a MZI;

FIG. 2D illustrates a top view of a third tunable laser embodiment of the present invention including a tunable element having two waveguides, a MZI and a reflective facet;

FIG. 2E illustrates a top view of a fourth tunable laser embodiment of the present invention including a tunable element having three waveguides and a reflective facet;

FIG. 2F illustrates a top view of a fifth tunable laser embodiment of the present invention including a SRFP tunable element having two waveguides, a ring resonator and a reflective facet;

FIG. 3 illustrates the intensity coming back from the tunable frequency element versus frequency of the exemplary embodiment of FIG. 2A;

FIG. 4 is a plot of the Mode Suppression Ration (MSR) versus the current in Amperes for the exemplary embodiment of FIG. 2A;

FIG. 5 is a plot of the output power in Watts versus the input current in Amperes for the exemplary embodiment of FIG. 2A;

FIG. 6A illustrates a laser class including two optical resonators on opposing sides of a gain medium;

FIG. 6B illustrates a laser including two SRFP optical resonators on opposing sides of a gain medium;

FIGS. 6C-6F are exemplary plots of the spectra of the light reflected from the resonator for different values of back reflections coefficients and high facet reflections;

FIG. 6G illustrates a further embodiment where one of the SRFP resonators is replaced by a ring resonator;

FIG. 7A illustrates a laser class including two optical resonators on the same side of a gain medium;

FIGS. 7B-7J illustrate various exemplary laser embodiments of the class of FIG. 7A; and

FIGS. 8A & 8B illustrate hybrid classes of the lasers of FIGS. 6A and 7A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

1. Semi-ring Fabry-Perot Resonator

FIG. 1A illustrates a novel optical resonator of the present invention. The resonator 100, a semi-ring Fabry-Perot (SRFP) resonator 100, comprises a medium 102 (such as a semiconductor material) including an edge forming a reflective facet 106 and a waveguide 104 within the medium, the waveguide having opposing ends 108A, 108B formed by the reflective facet 106. The resonator 100 behaves similar to a Fabry-Perot resonator with some additional advantageous properties. For example, manufacturing of the resonator 100 is simplified because only a single facet 106 is cut to produce...
the functional resonator cavity. In addition, due to this simplicity, the range of applications for a resonator 100 based on only a single facet 106 is also broader than for resonators requiring multiple facets; only one free facet is required to tune the resonator 100 in isolation from other elements of a given optical device. This foundational element can be used in a variety of optical devices, and is particularly useful in tunable laser applications. The resonator also has the advantage of a planar fabrication and not of requiring any grating structure or moving parts.

The resonator can be employed as a tunable element by constructing the waveguide 104 (or a portion thereof) such that the optical length is varied by controlled current injection as is known in the art. The current injection changes the index of refraction and therefore the optical length as the device is operated.

FIG. 1B illustrates the optical resonator 100 with the addition of a Mach-Zehnder interferometer (MZI) 110. The addition of the MZI 110 can be used to further enhance the performance and usefulness of the optical resonator 100. The MZI 110 includes an upper arm 112 and a lower arm 114 that are used to establish a path length differential for light entering the MZI 110. The remaining waveguide 116 (which can be considered a continuation of the waveguide 104) is used to couple the light to the reflective facet 106 at its end 106B. Also illustrated is a coupling region 114 which can be used to couple feedback from the resonator 100 to other elements in an optical device. It should be noted that the MZI 110 can be positioned on either side of the coupling region 114 in the resonator 100.

To describe intuitively the tunability mechanism one may look at the performance of the unbalanced MZI 110 and the SRFP resonator 100 individually and then in combination. For an ordinary Fabry-Perot cavity in a laser device, lasing is a function of the cavity optical length and typically only occurs near the top of the gain profile of the gain medium. Because adjustment of the cavity optical length is limited, there is no simple technique for tuning over a wide range. In addition, the cavity typically has a relatively broad gain profile, making it possible to have lasing at more than one frequency. In order to select a single frequency for operation, it is necessary to introduce a frequency selective mirror device.

FIG. 1C qualitatively illustrates a frequency selective mirror device 120 comprising a MZI 122 and mirror 124, such as a 100% mirrored facet. The MZI 122 alone produces a periodic frequency selectivity to the gain chip 126. Frequency tunability is obtained by changing the difference in optical length between the two arms 128, 130 of the MZI 122, which shifts the mode filtering spectrum of the MZI 122, and consequently changes the lasing mode of the laser 132. The change in the optical length can be induced altering the index of refraction of one or both of the waveguide arms 128, 130 through current injection.

Alternately (or in conjunction with tuning by current injection) tuning may be achieved by changing only the phase of the coupling coefficient. Thus, the resonant frequencies of the device to tune the device. So in order to tune the device, it is not required to change the optical length of the resonator. Tuning of the device can also be obtained by techniques which change the phase of the coupling coefficient.

FIG. 1D qualitatively illustrates the reflection output of the frequency selective mirror device 120 using the MZI 122 with respect to frequency. The cavity modes of the laser 132 are also illustrated. However, the MZI 122 has very low finesse. For a given device length, larger free spectral range (FSR) results in a larger tuning range, but at the expense of the selectivity between the main and the side modes. It should noted that devices similar to the one shown in FIG. 1C do not have high MSR due to the low finesse of the MZI (e.g., as in a known Y-branch laser). The MZI 122 used alone therefore does not often provide adequate selectivity. To significantly improve performance, an increase in the MSR while maintaining the wide tuning range is necessary. To obtain this, requires a more selective filtering method. The combination of the SRFP resonator 100 with an MZI 110 as shown in FIG. 1B provides the needed selectivity.

FIG. 1E illustrates the reflectance of the SRFP resonator 100. The SRFP is analyzed in detail in the next section. The behavior of the SRFP resonator 100 can be simulated by a Fabry-Perot cavity. However, the SRFP resonator 100 has the advantage over a standard Fabry-Perot cavity resonator due to the use of only single facet 106 reflectivity. This eases the fabrication of the resonator 100 because the length of the SRFP resonator 100 is disassociated from that of the chip. The FSR of the SRFP resonator 100 is not constrained by fabrication requirements, as it is in the case of a standard Fabry-Perot cavity resonator.

The SRFP resonator 100 also possesses advantages over a standard ring resonator through its support of standing waves. This allows the SRFP resonator 100 to use only one coupling region 114 in order to couple light from the SRFP resonator 100 back to a gain medium in an optical device. FIG. 1F qualitatively illustrates the combined response of the MZI 110 and the SRFP resonator 100. As shown in FIGS. 1D–1F, the SRFP resonator 100 parameters can be chosen such that the peaks of the SRFP resonator 100 correspond to the peak of the MZI 110 filter, which also corresponds to a cavity mode of the SRFP resonator 100. This main mode, mode 0, will be the lasing mode. Notably, the benefit of the MZI 110 is enhanced by its inclusion within the SRFP resonator 100; conventionally a MZI would be added external to an ordinary Fabry-Perot resonator.

In order to better understand the operation of the SRFP resonator 100 and MZI 110 filter combination, a worst case can be visualized in which only one of the SRFP resonator 100 peaks correspond to a cavity mode (although other cavity modes may also exist at frequencies between the resonator peaks). The SRFP resonator 100 should be designed in a manner to reduce the strength of all the cavity modes between the main mode and the next SRFP resonator peak. The MZI 110 parameters are now selected to ensure that the next SRFP peak becomes the side mode. Referring to FIG. 1E, we note that for the SRFP, if mode 0 is the lasing mode, mode 1 the next cavity mode and mode 4 the cavity mode which is aligned with the next peak of the ring, after adding the MZI filter inside cavity, mode 4 becomes the side mode of the combined device, as shown in FIG. 1F. In the case of the MZI alone, mode 1 is the side mode as shown in FIG. 1D. With this implementation, therefore the MSR is no longer a function of the ratio of mode 0 over mode 1 but it is a function of the ratio of mode 0 over mode 4, making the MSR is a function of the SRFP resonator FSR and MZI gain envelope. The next section presents the theoretical analyses of an exemplary device supporting the foregoing discussion.

2. Exemplary Embodiments of a Laser Using an SRFP Resonator

FIG. 2A illustrates a top view of a tunable laser embodiment of the present invention including a SRFP tunable element having two waveguides, a MZI and a reflective facet. The tunable laser device 200 comprises a tunable feedback element 202 within a Fabry-Perot cavity 204. The
tunable feedback element 202 comprises an optical resonator as described above, a semi-ring Fabry-Perot resonator. The cavity 204 can be defined the gain (active) medium 206 within a waveguide bounded by reflective facets, a rear facet 208 and a front 210 at opposing ends of the gain medium 206. The rear facet 208, bounding one end of the cavity 204, can include an anti-reflection coating. The front facet 210, bounding the opposing end of the cavity 204, comprises the output of the tunable laser device 200.

The coupling region 212 couples the gain medium 206 and the tunable feedback element 202. In the exemplary embodiment shown, the coupling region 212 is disposed within the gain medium 206 and provides an input and output normalized complex field amplitude from each side of the coupling region 212 to the gain medium 206 toward rear facet 208 on one side and toward front facet 210 on the opposite side. Similarly, the tunable feedback element 202 also receives an input and output normalized complex field amplitude from each side of the coupling region 212 to a first waveguide 214 on one side and to a second waveguide 216 on the opposite side.

In this first exemplary embodiment, the tunable feedback element 202 comprises a Mach-Zehnder interferometer (MZI) 218. The first waveguide 214 of the tunable feedback element 202 provides a path from the coupling region 212 to a high reflection rear facet 220 of the passive medium. The second waveguide 216 of the tunable feedback element 202 provides a path from the coupling region to a first end the MZI 218. The MZI 218 includes an upper arm 222 and a lower arm 224. That are used to establish a path length differential for light entering the MZI 218. The opposite end of the MZI 218 is coupled to a third waveguide 226 that provides a path from the MZI 218 to the high reflection rear facet 220 of the passive medium. It should be noted that the two waveguides of the described embodiment refer to the first waveguide 214 on one side of the coupling region 212 and the combination of the second and third waveguides 214, 226 that are interrupted by the MZI 218 on opposite of the waveguide 214 and the second waveguide 214 coupled directly to the rear facet 220.

It should be noted that facets 208, 210 and 220 are generally formed from each entire respective surface of the device 200. This greatly simplifies the manufacturing process. Thus, rear facet 220 of the passive medium can be formed from the edge surface of the device 200 adjacent to both the surfaces of rear facet 208 of the active medium and front facet 210 of the active medium of the cavity 204. Similarly, the front facet 228 of the passive medium can be formed from the entire edge surface opposite the rear facet 220.

The coupling region 212 between the gain medium 206 and the tunable feedback element 202 can be modeled as follows using a similar approach as in A.Yariv, “Universal relations for coupling of optical power between micro resonators and dielectric waveguides,” Electronics Letters, vol. 36, page 321, 2000, which is incorporated by reference herein, the gain-tunable element coupling region 212 as shown in FIG. 2A, where a, and b, are the input and output, respectively, normalized complex field amplitudes entering and leaving the coupling region 212. Under the condition of lossless coupling, that is,

\[
|K_2(f)|^2 + |K_1(f)|^2 = 1
\]  

The complex field amplitudes satisfies the following set of equations,

\[
\begin{align*}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} & = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}

d_1

d_2

d_3

d_4

\end{align*}
\]  

where \( f \) is the frequency of the field, \( t_1(f), t_2(f) \) and \( K_1(f) \), \( K_2(f) \) are the transmission and coupling coefficients of the complex field region, respectively. The set of equations (2) can be also written in the matrix form.

The tunable feedback element 202 shown in FIG. 2A can be analyzed as follows. In the structure of FIG. 2A,

\[
\begin{align*}
\begin{bmatrix}
a_1 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix} & = \begin{bmatrix}
R_1 & \frac{A_1}{2} e^{j\phi_1} f(n_a L_a - n_b L_b) & -r_1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
d_1 \\
d_2 \\
d_3 \\
d_4 \\
d_5 \\
d_6 \\
d_7 \\
d_8 \\
\end{bmatrix}
\end{align*}
\]

where \( A_1 = |\alpha|^2 |\beta|^2 f^2 |\gamma|^2 |\delta|^2 |\epsilon|^2 |\rho|^2 \),

\[
\begin{align*}
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} & = \begin{bmatrix}
\frac{1}{2} e^{j\phi_1} f(n_a L_a - n_b L_b) & -r_2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\end{align*}
\]  

where \( \alpha, \beta, \gamma, \delta, \epsilon, \rho \) are the loss per unit length, the refractive index and the length of the waveguide 216 and \( \alpha_1, n_0, \beta_1 \) and \( \beta_2 \) are the corresponding quantities for the waveguide 226. and \( \gamma_1, \delta_1, \epsilon_1, \rho_1 \) are respectively the refractive index and the length of the upper arm 220 of the MZI 218 and \( \gamma_2, \delta_2, \epsilon_2, \rho_2 \) are the corresponding quantities for the lower arm 222 of the MZI 218.

Since the two waveguides 214 of the passive medium are an anti-reflection coating, \( a_1 = 0 \). From equations (3), (4) and (5), one can determine,

\[
\begin{align*}
\begin{bmatrix}
b_1 \\
b_2 \\
b_3 \\
b_4 \\
b_5 \\
b_6 \\
b_7 \\
b_8 \\
\end{bmatrix} & = \begin{bmatrix}
R_1 & \frac{A_1}{2} e^{j\phi_1} f(n_a L_a - n_b L_b) & -r_1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \begin{bmatrix}
d_1 \\
d_2 \\
d_3 \\
d_4 \\
d_5 \\
d_6 \\
d_7 \\
d_8 \\
\end{bmatrix}
\end{align*}
\]

where

\[
\begin{align*}
R_1 & = \frac{R_1(e^{j\phi_1} f(n_a L_a - n_b L_b) + r_1)}{1 - R_1(e^{j\phi_1} f(n_a L_a - n_b L_b) + r_1)}
\end{align*}
\]

In the case of a tunable laser for WDM applications, one can neglect the frequency dependence of the coupling region over the working frequency range to obtain a rough approximation. Accordingly, it follows that,
through MZI 218 as shown. However, in this embodiment the MZI 118 is structured with the upper arm 222 of the MZI work, similar analysis can be rendered for the following respecting FIG. 1A. Applying the foregoing analytic frame-the following result is obtained.

The ring resonator waveguides 214 and 216 are coupled back into waveguide 216 through the MZI 218 as shown.

FIG. 2B illustrates a top view of a third tunable laser embodiment of the present invention including a tunable element having two waveguides 214, 216, a MZI 218 and two reflective facets 208 and 220. This embodiment 250 is similar to that of FIG. 2A, however, the first waveguide 214 is coupled to the rear facet 208 of the active medium rather than the rear facet 220 of the passive medium. This embodiment 250 of the invention illustrates a hybrid based on the semi-ring Fabry-Perot resonator of FIG. 1A. This embodiment couples a first waveguide 214 and second waveguide 216 from coupling region 212 to different reflective facets. The second waveguide 216 is coupled to the rear facet 220 of the passive medium through the MZI 218 and a third waveguide 226. As defined herein, in a semi-ring Fabry-Perot resonator, two ends of a waveguide 104 are coupled to a common facet 106 shown in FIG. 1A. Thus, at least some of the advantages, e.g., manufacturing simplicity, are not afforded by the embodiment of FIG. 2D. However, a difference in the reflective facets is afforded by the embodiment of FIG. 2E. The invention is not limited to the specific examples shown.

FIG. 2E illustrates a top view of a fourth tunable laser embodiment 260 of the present invention including a tunable element having three waveguides 262, 264 and 266 and a reflective facet 220. This embodiment 260 is another hybrid based on the semi-ring Fabry-Perot resonator of FIG. 1A in combination with a ring resonator. In this case, a first waveguide 262 and a second waveguide 264 are coupled from coupling region 212 to the rear facet 220 of the passive medium. In addition, a third waveguide 266 couples the two waveguides 262 and 266. The invention is not limited to the specific examples shown.

FIG. 2F illustrates a top view of a fifth tunable laser embodiment 270 of the present invention including a SFRP tunable element having two waveguides 272, 274, a ring resonator 276 and a reflective facet 220. This ring resonator 276 included within the SFRP resonator (comprising the two waveguides 272, 274 and the reflective facet 220) of the tunable element 202 and coupled to the SFRP resonator by the second coupling region 278. Although the ring resonator 276 is shown positioned on the waveguide 274, the tunable element 202 can alternately be structured with the ring resonator 276 on the waveguide 272. Other equivalent structures are also possible.

The SFRP provides a first set of resonator frequencies and the ring resonator provides another set of resonator frequencies. The combined resonant frequency of the tunable element 202 will be the ones which coincide with both the ring and the SFRP. Also, it should be noted that the effect of a back reflection (r1=0) for the embodiment 270 shown in FIG. 2F is to improve the performance of the resonator in terms of reflection (b3ia3) and FSR (which is defined as the spacing between two consecutive peaks of same intensity). This embodiment 270 may increase the FSR of the resonator and the SRFP. Also, it should be noted that the effect of a back reflection (r1=0) for the embodiment 270 shown in FIG. 2F is to improve the performance of the resonator in terms of reflection (b3ia3) and FSR (which is defined as the spacing between two consecutive peaks of same intensity). This embodiment 270 may increase the FSR of the resonator and be merely changing the back reflection (r1) instead of the resonator length.

4. Engineering a Single SFRP Tunable Laser

A general analysis of a single tunable frequency mirror (a semi-ring Fabry-Perot resonator) is presented above. This section is concerned with the engineering of the tunable frequency mirror together with the gain section in order to
produce a widely tunable single-mode laser as described in FIG. 2A. Although embodiments of the invention can be constructed as hybrid devices with distinct elements separately fabricated and integrated together, the invention can advantageously be used to form optical devices through monolithic fabrication, in a simpler, cost effective manner.

One can examine a specific design in which the active medium is a III-V material system operating at approximately 1.55 μm wavelength. For this specific exemplary numerical application, a MZI free spectral range (FSR) of approximately 1.248 GHz (equivalent to a tunability range of approximately 1.248 GHz (10 nm)) is chosen. A fine wavelength selection of approximately 50 GHz is considered. This is the frequency difference between two consecutive frequencies of the laser channels and, in turn, corresponds to the total combined length of waveguide 114, waveguide 116 and waveguide 124 of approximately 1 mm.

It can also be assumed that the gain medium is substantially removed from the tunable filter so that the waveguide loss reaches a maximum value of approximately 10 dB/cm, r1, r2 and r3 are substantially equal and equal to approximately 0.97, and K1 and K2 are substantially equal and equal to 0.7. The main reflection of the tunable filter is taken to correspond to a cavity mode, which is the laser mode. The 10 dB/cm loss is applied as a worst case estimate for evaluation purposes; realistic losses are significantly lower in many applications, depending upon manufacturing and other considerations.

Referring to FIG. 2A, it is also assumed that the separation of the cavity modes is such that the reflection of the adjacent cavity mode from the tunable filter element 202 is lower than that of the cavity mode, coinciding with the next strongest reflection peak of the tunable filter element 202. In the calculation of the MSR, a worst scenario is assumed in which both the strongest and next strongest field reflection peak spectrum of the tunable filter element 202 correspond to a cavity mode. The contribution of the filter reflection to the energy stored in each mode only is included in order to calculate the single contribution of the tunable filter element 202 in the MSR. This means that these calculations represent a pessimistic view where the same gain is present both for the main and side mode. In reality, this is not the true case and the gain is relatively flat for the side mode.

FIG. 3 illustrates the intensity coming back from the tunable frequency element versus frequency of the exemplary embodiment of FIG. 2A. A fine wavelength selection FSR of approximately 50 GHz and a MZI FSR of approximately 1.248 GHz are applied. In addition, an intensity coupling between the gain-tunable element of approximately 0.49 and a waveguide loss of approximately 10 dB/cm is also used.

The considered gain medium parameters of the exemplary embodiment of FIG. 2A are approximately 0.2 μm thickness, 3 μm width, 300 μm length and a material loss of approximately 80/cm. The gain versus carrier density characteristic of the active medium is associated with a transparency carrier of approximately 5x10<sup>15</sup> cm<sup>-3</sup>.

According to L. Coldren et al., "Diode Lasers and Photonic Integrated Circuits", p. 45, 1995, which is incorporated by reference herein, the threshold current is given by,

\[ I_b \approx \frac{g VN_\text{th}^2}{\eta} e^{\frac{Z(\alpha_i + \alpha_m + \alpha_t)}{q}} \]  

where \( V \) is the volume of the device, \( \eta \), the quantum efficiency (in our case its value is approximately 0.7), \( N_\text{th} \) is the transparent coefficient of approximately 2x10<sup>18</sup> cm<sup>-3</sup>, \( \alpha_i \) is the gain medium intrinsic loss, (approximately 80 cm<sup>-1</sup>), \( B \) the bimolecular recombination coefficient (usually B<sup>-1</sup> ~ 10<sup>-10</sup> cm<sup>3</sup>/s for most III-V materials of interest). A passive waveguide loss of approximately 10 dB/cm, a confinement factor \( \Gamma \) of approximately 0.7 and a differential gain \( g_m \) of approximately 5x10<sup>-16</sup> cm<sup>2</sup>/A are also applied. The mirror loss \( \alpha_m \) is given by the following

\[ \alpha_m = \frac{1}{\text{waveguide medium}} \left( \frac{1}{r \Gamma} \right) \]  

where,

\[ r = \left| \frac{b_1}{a_1} \right| \]  

and \( r \) is the reflectivity from the strongest peak of the tunable frequency mirror, \( r = 0.3922 \) is the output facet field reflectivity of the tunable laser 100.

FIG. 4 is a plot of the Mode Suppression Ratio (MSR) versus the current in Amperes for the exemplary embodiment of FIG. 1B. According to L. Coldren et al., p. 107, Ibid., the Mode Suppression Ratio (MSR) can be given by,

\[ \text{MSR(dB)} = 10 \log_{10} \left[ \frac{\Delta a + \Delta g}{\partial G} + 1 \right] \]  

where \( \Delta a \) is the separation between the mirror loss and the net modal gain for the main mode and is given by,

\[ \frac{\Delta a}{I-I_\text{th}} = 10^{-3} \frac{I}{I-I_\text{th}} \text{ cm}^{-1} \]  

\[ \Delta a = 91.4 \text{ m}^{-1} \]  

\[ \Delta g = 0 \]  

is the loss margin and \( \Delta g = 0 \) is the modal gain margin. Proceeding in this way, \( I_\text{th} = 20.2 \text{ mA} \).

FIG. 5 is a plot of the output power in Watts versus the input current in Amperes for the exemplary embodiment of FIG. 1A. The output power is given by L. Coldren et al., p. 42, Ibid.

\[ P_\text{o} = \frac{g_m}{(a_1 + \alpha_m)} \frac{h v}{q} (I-I_\text{th}) \text{ for } I > I_\text{th} \]  

where \( h \) is Planck’s constant.

5. Exemplary Embodiments of a Laser Using Multiple Resonators

Further embodiments of the invention comprise laser structures employing multiple optical resonators. The novel SRFP resonator is particularly useful in some of the laser structures described hereafter. Two foundational classes of laser embodiments are described herein, a class of laser including two optical resonators on opposing sides of a length of gain medium where one of the resonators is an SRFP resonator and a novel class of laser including two optical resonators on the same side of a length of gain medium. Further hybrids of these two classes are described
as three or four optical resonators used in combinations on opposing sides of a length of gain medium. As with the single SRFP and other laser embodiments above, these embodiments can be monolithically fabricated.

5.1 Using at Least One SRFP Resonator With Resonators on Opposite Sides of the Gain Medium

FIG. 6A illustrates a class of laser 600 including two optical resonators 602A, 602B on opposing sides of a length of gain medium 606, i.e. the towards the left and right ends of the gain medium 606. Previous lasers have employed a gain medium bounded by optical resonators such as gratings. However, in embodiments of the present invention, at least one of the optical resonators 602A, 602B comprises a SRFP resonator as previously described. This defines a novel class of monolithic tunable semiconductor lasers. The lasers use the Vernier effect for the tunability. The nature of the coupling is not critical for the analytical study of the laser 620. The gain medium 606 provides light amplification. Each SRFP resonator 622A, 622B cavity includes waveguides {q} and {q+2} with q={2,5}. These correspond to the left and right portions of each of the waveguides 624A and 624B from their respective coupling regions 604A and 604B. Each respective facet is the high reflection facet q 626A, 626B. Each SRFP resonator 622A, 622B has a uniform peak transmission at all resonant peaks. Their FSR is related to their optical length.

The two SRFP have slight different optical length, thus providing the mode selection and the wavelength tuning mechanism. Therefore, the two SRFP resonator 622A, 622B tuning technique (which is based on the Vernier technique) is achieved by aligning the peaks in the two sets of resonator combos with the adjustment of index in one or both SRFP resonators 622A, 622B.

The proposed device can be compared to both the known sampled grating-distributed Bragg reflector (SG-DBR) laser and to the double ring resonator coupled laser (DR-RCL). However, in the laser 620 uses SRFP resonators 622A, 622B on opposing sides of the length of gain medium 606. In contrast, SG-DBR lasers employ sampled gratings on opposite sides of a length of gain medium and DR-RCL uses ring resonators on opposite sides of a length of gain medium.

One advantage of the SRFP resonator over the standard ring resonator is its support of standing waves (and larger waveguide bending curvature as previously discussed). This allows the device the use of only one coupling region in order to couple light from the SRFP resonator back to the gain medium. Further, the advantage of the SRFP resonator over the standard Fabry-Perot resonator is the use of only one facet. This eases the fabrication constraints on the SRFP resonator; the length of the SRFP may greatly differ from that of the chip.

Thus, the FSR of the SRFP resonator is not strongly dictated by fabrication requirements as with conventional Fabry-Perot resonators. As SRFP resonators produce a substantially uniform peak transmission at all resonant peaks, the uniform thresholds and efficiencies between the different operating wavelengths are substantially the same. Consequently, the laser 620 of FIG. 6B and the DR-RCL are nearly analytically equivalent and, accordingly, the laser 620 should exhibit at least the same advantages in term of performance (such as tunability and MSR) as the DR-RCL if manufactured properly. In addition, the laser 620 exhibits additional positive features. For example, the laser 620 allow a reduction in the number of coupling regions as well as the elimination of absorption regions. Indeed, reflection problems related to the discontinuity between the absorption region and the passive waveguide in DR-RCL devices are avoided. The presence of a non perfect high reflection facet (i.e. r4=0) does not appreciably deteriorate the resonator response. Also, as previously mentioned, the overall design has the advantage of planar fabrication and does require any grating structure or moving parts.

Analysis and modeling of the coupling between the gain medium and the resonator in the laser 620 build on the analysis related to the SRFP resonator, in section 2 above.
The matrix form normalized complex field amplitude equations for coupling region 604A is as equation (3) in section 2, above. Similarly, the matrix form normalized complex field amplitude equations for coupling region 604B is as follows.

\[
\begin{align*}
\begin{pmatrix}
 b_s \\
 b_p \\
 b_n \\
 b_q
\end{pmatrix} &=
\begin{pmatrix}
 0 & 0 & a_6(f) & K_6(f) & a_6 \\
 0 & 0 & -K_6(f) & a_6(f) & a_6 \\
 a_6(f) & K_6(f) & 0 & 0 & a_6 \\
 -K_6(f) & a_6(f) & 0 & 0 & a_6
\end{pmatrix}
\begin{pmatrix}
 a_6 \\
 a_6 \\
 a_6 \\
 a_6
\end{pmatrix}
\end{align*}
\]

In the structure of FIG. 6B, from equations (3) and (27),

\[
\begin{align*}
\frac{b_2}{a_2} &= -K_1^2 R_3 [r_N + K_2] + K_1 R_3 [-K_2^2 N + r_1] \\
\frac{b_4}{a_4} &= -K_4 R_1 [r_N + K_2] + K_1 R_3 [-K_2^2 M + r_1],
\end{align*}
\]

where,

\[
\begin{align*}
R_1 &= e^{j2n_i L_i}, \quad R_3 = e^{j2n_i L_i}, \\
M &= \frac{R_1 R_3 K_2 + R_2 R_4 K_2}{1 - R_1 R_2 K_2 + R_2 R_3 K_2 - R_1 R_4 K_2 + R_4 R_3 K_2}
\end{align*}
\]

where \(a_n, n_i, L_i\) are, respectively, the loss per unit length, the refractive index and the length of the waveguide \(i\) and \(r_i\) is the field reflectivity of the different facets as shown in FIG. 6B.

In the case of a tunable laser for WDM applications, one can neglect the frequency dependence of the coupling region over the working frequency range to obtain a rough approximation. Accordingly, it follows that,

\[
K_i = |K_i| e^{j\theta_i}, \quad \theta_i = |\theta_i| e^{j\phi_i}
\]

FIGS. 6C–6F are exemplary plots of the spectra of the light reflected from the resonator for different values of the back reflection coefficients (r1, r8), and high facet reflections (r2, r4, r5, r7). These plots demonstrate the effect of the coupling coefficient and the back reflection (that is r1 or r8) on the laser 620. FIG. 6C represents b3/a3 versus wavelength in the case where K1=K2=0.7 and r1=0.4, and a high reflection facet, r2=1. FIG. 6D represents b3/a3 versus wavelength in the case where K1=K2=0.7 and r1=0.7, and a high reflection facet r2=0.9. FIG. 6E represents b3/a3 versus wavelength in the case where K1=K2=0.7 and r1=0.1, and the high reflection facet r2=0.9. FIG. 6F represents b3/a3 versus wavelength in the case where K1=K2=0.7 and r1=0.4, and the high reflection facet r2=0.9.

Notably, FIG. 6E shows that presence of a non perfect high reflection facet (r1=0, r8=0) does appreciably deteriorate the resonator response. Also, as shown in FIG. 6F, the effect of a back reflection (r4) is to improve the performance of the resonator in term of reflection b3/a3 and FSR (the spacing between two consecutive peaks of same intensity). Thus, the laser 620 offers the possibility of increasing the FSR of the resonator by merely changing the back reflection (r4) instead of the resonator length. Also, even if there is a reflection returning to the gain medium directly from the coupling region, the laser 620 will operate correctly up to the point where this is equal to the reflection returning from the filter b3/a3.

FIG. 6G illustrates a further embodiment where one of the SRFP resonators is replaced by a ring resonator 628. Other alternate structures are also possible with at least one SRFP resonator on one side of the gain medium and another resonator form on the opposite side.

5.2 Using Multiple Resonators on One Side of the Gain Medium

FIG. 7A illustrates a laser 700 including two paired optical resonators 702A, 702B on the same side of a gain medium. One of the drawbacks of many prior art lasers comprising resonators bounding a gain medium (excluding those employing at least one SRFP resonator described above) is that they may exhibit relatively low power levels due to the resonators, such as gratings, employed on both sides of the device. In such prior art lasers, each resonator is designed to reflect most of the light coupled into the resonator back to the gain medium. Consequently, the amount of the light coming out of the device is weak. In contrast, the laser 700 employs two paired optical resonators 702A, 702B on one side of the gain medium 706 and leaves the output facet 704 of laser 700 as a cleaved facet.

The Vernier techniques can still employed to provide tuning in the laser 700. Tuning of the class of devices described by FIG. 7A can be obtained by changing the resonator frequencies of at least one of the resonators. However, in order to be able to use the Vernier technique, the field from the gain medium 706 must travel between both resonators 702A, 702B before returning to the gain medium 706. Accordingly, a 3 by 3 coupling region 708 can be employed to accomplish this. The coupling region 708 couples light from the gain medium 706 to the resonators 702A, 702B and the gain medium 706 and from one resonator, e.g. 702A, to the other resonator, e.g. 702B, and the gain medium 706. For example, the coupling region 708 can be for example a 3*3 MMI coupler. The class of lasers of FIG. 7A have the advantage of providing both high MSR, high tunability and high power in a single laser device.

In further embodiments of the invention, either or both the resonators 702A, 702B can be either SRFP resonator. In the case of SRFP resonators, which employ side facets 710A, 710B, this allows separate adjustment and design of each resonator 702A, 702B. Further, each SRFP can optionally include a MZI inside the resonator. In this case, as previously discussed, the free spectral range (FSR) of the resonator is increased because the FSR is substantially equal to that of the included MZI. Tuning can be obtained by changing the difference of optical length of the MZI. In addition, in still further embodiments, either resonator 702A, 702B can be ring resonator. Some exemplary embodiments of the class of lasers of FIG. 7A are shown in FIGS. 7B–7J as follows.

FIG. 7B illustrates a top view of an exemplary laser embodiment 720 where the resonators 702A, 702B comprise SRFP resonators 712A, 712B. In general, the coupling region 708 can be designed to couple light from the two resonators 702A, 702B and the gain medium 706, i.e. light coming from one resonator, e.g. 702A, is coupled to the other resonator, e.g. 702B and the gain medium 706. Only the field which is both a resonator mode of the combination of resonator 702A, resonator 702B and the coupling region 708 is reflected back to the gain medium 706. Tuning can be obtained by changing the resonator modes of resonator 702A or resonator 702B or the modes of both resonators 702A,
The optical device of claim 1, further comprising a third facet intersecting the second waveguide and adjacent to the first facet.

The optical device of claim 1, wherein the first waveguide and the second waveguide comprise a substantially symmetrical arrangement about a line normal to the first facet through the coupling region.

The optical device of claim 1, wherein the first waveguide includes a Mach-Zehnder interferometer.

The optical device of claim 1, wherein current injection is used to adjust an optical length of at least a portion of the first waveguide.

The optical device of claim 1, wherein the second waveguide intersects both the opposing Fabry-Perot reflective facets.
12. The optical device of claim 1, wherein the first waveguide and the first facet operate as an optical resonator.
13. The optical device of claim 12, wherein the optical resonator comprises a tunable element of the optical device.
14. The optical device of claim 13, wherein current injection is used to adjust an optical length of at least a portion of the first waveguide to tune the tunable element of the optical device.
15. An optical device comprising:
   a first waveguide means for carrying light within a medium including an edge forming a first facet that is reflective, the first waveguide means having first opposing ends formed by the first facet;
   a second waveguide means for carrying the light where the second waveguide means avoids intersecting the first facet and has both of second opposing ends formed by facets other than the first facet; and
   a coupling region means for coupling the light between the first waveguide and the second waveguide.
16. The optical device of claim 15, further comprising a second facet intersecting the second waveguide means and adjacent to the first facet.
17. The optical device of claim 15, wherein the first waveguide means and the second waveguide means comprise a substantially symmetrical arrangement about a line normal to the first facet through the coupling region means.
18. The optical device of claim 15, wherein the first waveguide means includes a Mach-Zehnder interferometer.
19. The optical device of claim 15, wherein current injection is used to adjust an optical length of at least a portion of the first waveguide means.
20. The optical device of claim 15, wherein the medium is formed into a Fabry-Perot cavity having opposing Fabry-Perot reflective facets adjacent to the first facet and the second waveguide means intersects both the opposing Fabry-Perot reflective facets.