ABSTRACT

Utilizing round optical fibers as communication channels in optical communication networks presents the problem of obtaining a high efficiency coupling between the optical fiber and the laser. A laser is made an integral part of the optical fiber channel by either diffusing active material into the optical fiber or surrounding the optical fiber with the active material. Oscillation within the active medium to produce lasing action is established by grating the optical fiber so that distributed feedback occurs.
FIELD OF THE INVENTION

This invention generally relates to distributed feedback lasers. More particularly, the present invention pertains to optical fiber lasers utilizing distributed feedback.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 4 is a perspective view of a broken-away portion of a machined optical fiber that is used in the present invention.

FIG. 5 is a perspective view of a broken-away portion of a fiber configuration that is analytically equivalent for certain propagation modes to the machined fiber of FIG. 4.

FIG. 6 is a graph illustrating the performance parameters of the laser mechanism of FIG. 2.

FIG. 7 is a graph illustrating the performance parameters of the laser mechanism of FIG. 3.

FIG. 8 is a graph illustrating the performance parameters of the laser mechanism of FIG. 2 when considering an alternate transmission mode.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring first to FIG. 2, which illustrates a preferred embodiment of the present invention, a laser device 43 is made an integral part of an optical communication line 33. The laser mechanism comprises a certain length of the optical fiber 33, from one end thereof, being doped with an active material 41 such as, neodymium or an organic dye. A grating 34 is micromachined into the optical fiber 33 at a precise depth 37 and displacement 35 along that length. A polychromatic energy source 31 may be spirally wound around the end of the optical fiber 33 that contains the active medium to provide the pumping energy required to produce population inversion in the active medium. The polychromatic radiator could take the form of a discharge lamp with a cylindrical reflector therearound (not shown). An alternate source of pumping energy that may be utilized is a xenon lamp with an ellipsoidal reflector (not shown). A power source 29 provides energy for the pumping source 31.

FIG. 3 illustrates an alternate preferred embodiment of the laser mechanism of this invention as comprising, a laser mechanism 45 that is an integral part of an optical fiber communication line 53. The laser mechanism comprises a certain length at one end of the communication fiber 53 being grated with gratings that have a specified depth 57 and width 55. The grating length of the fiber is inserted in a bath of active material 51 which may be either in a gaseous or liquid state such as, a liquid solution of neodymium oxide (Nd2O3) dissolved in sodium oxycarbide (SeOCl2) acidified with tin tetrachloride (SnCl4). Other types of lasing solutions that may be used are solutions of fluorescent dyes such as, rhodamine for example, in liquids such as, ethyl alcohol.

Instead of immersing the grated end of fiber 53 in a liquid bath of active material, a solid active material may be deposited, by sputtering for example, around the grated optical fiber 53.

A source of polychromatic radiation 49 may be spirally wound around the end of the optical fiber 53 having the active material therearound to provide the pumping energy required for population inversion within the active medium.

FIG. 4 presents a perspective view of a portion of a machined glass rod that is part of the laser mechanism. This portion 61 has grooves 63 micromachined therein that have a certain depth 67 and occur in a certain periodicity 65. Photore sist and ion-milling techniques are known that will produce gratings 59 with a periodicity of approximately 0.2 microns at a peak-to-peak height of approximately 0.1 micron. A report on such a
where: $\eta = (d/r) (D/2a)^{1/2}$

$d = $ depth of surface corrugation, and $d << a$. 

The effective gain coefficient and the coupling coefficient for TE modes in a circular waveguide, can be evolved as follows. In case of TE propagation, the normalized electric field is given by:

$$ E_r = E_z = 0 $$

$$ E_\theta = [J_1(sr)/J_1(sa)] \exp(i\beta z - i\omega t) \text{ where } r < a $$

$$ E_\theta = [K_1(\delta r)/K_1(\delta a)] \exp(i\beta z - i\omega t) \text{ where } r > a $$

where $J$ is the Bessel function and $K$ is the modified Bessel function. The magnetic field can then be derived from Maxwell's equations. The corresponding dispersion relations are:

$$ \delta K_1(sa)/K_1(\delta a) = -s J_1(sa)/J_1(sa) $$

$$ -\delta^2 + \beta^2 = \epsilon_0 \beta^2 $$

$$ s^2 + 1 = \epsilon_0 k^2 $$

where $s$ and $\beta$ are the wavevectors, $\epsilon = \omega/c$ and $\epsilon_0$, $\epsilon_a$ are the relative dielectric constants in the fiber and the surrounding material.

Assuming that an active medium has a gain coefficient $G$, whether the optical fiber contains the active medium or the active medium is surrounding the optical fiber, the effective gain coefficient will be $CG$. The efficiency coefficient can be computed by taking a complex dielectric constant and solving equations 4, 5 and 6 for $\beta$, which is now complex. For the small gain case, the well known Taylor development will produce:

$$ C = (k \sqrt{s \beta}) \left[ \frac{1}{1 + F} \right] $$

for a fiber doped with an active medium, and

$$ C = (k \sqrt{s \beta}) \left[ \frac{1}{1 + F} \right] $$

for a fiber surrounded by an active medium where $F = (1 - J_1 J_1^*)/(1 - K_0 K_0^*)$.

The same expression for the efficiency coefficient in equation No. 7 above, can be derived from the relation:

$$ C = k \sqrt{s \beta} \left( \frac{P_i}{P_T} \right) $$

Where $P_i$ is the power in the fiber and $P_T$ is the total power. The first term in equation No. 9 expresses the fact that the optical ray travels a zig-zag line in the guide.

The coupling coefficient between the different TE modes due to the surface corrugations machined into the optical fiber can be determined by using the fact that the surface corrugation is equivalent to a periodic surface current. The coupling coefficient between the pth and qth mode is:
The prime value of \( K_i \) and \( J_1 \) corresponds to a derivation relative to the argument.

The threshold gain required to produce lasing action in a distributed feedback structure can be determined by using a modified form of the Kogelnik and Shank approach described in their above noted article. The modification would be necessary to take into account the fact that the coupling between two waves could have different effective gains and group velocity. Making reference now to the graphs of Figs. 6, 7 and 8, it should be remembered that only the longitudinal mode of propagation closest to the Bragg frequency is being considered.

FIG. 6 illustrates the relationship between the coupling coefficient \( XL \) curve 91, the efficiency coefficient \( C \) curve 93 and the threshold gain GL curve 89 as a function of the operating wavelength \( \lambda \) for the 0-0 mode of propagation in the laser structure shown in FIG. 2. X axis 85 illustrates an increasing frequency from left to right as the wavelength of the photon energy emitted from the active medium decreases. Y axis 83 illustrates an increasing coupling coefficient \( XL \) and efficiency coefficient \( C \) from bottom to top. The other Y axis 87 illustrates an increasing threshold gain GL from bottom to top. The L in the coupling coefficient \( XL \) and the threshold gain GL represents the length of the corrugations in the optical fiber.

From the curves of FIG. 6, it is seen that near cut-off the efficiency coefficient \( C \) curve 93, and the coupling coefficient \( XL \) curve 91 is very small. The threshold gain GL curve 89 starts at a very high value near cut-off and decreases to a minimum as the coupling coefficient \( XL \) curve 91 increases. The threshold gain GL curve 89 starts to increase again as the coupling coefficient \( XL \) curve 91 decreases.

The coupling coefficient \( XL \) curve 91 is small near cut-off because the energy is spread mostly in the area surrounding the fiber. At high frequency the coupling coefficient \( XL \) is small because the energy is confined in the fiber with a very small field at the periphery. The coupling reaches a maximum somewhere in between cut-off and high frequency. The efficiency coefficient \( C \) curve 93 is close to one when the energy is mostly in the active region and close to zero when the energy is mostly outside the active region. In the case of FIG. 6, the curves represent a doped optical fiber having the active material within the fiber. The efficiency coefficient \( C \) curve 93 will, therefore, be zero near cut-off, because the energy is mostly in the area outside the fiber, which is outside the active medium. It increases, and gets closer to one, the higher the frequency gets because the energy begins to be concentrated within the fiber in the active medium.

FIG. 7 illustrates the relationships of the coupling coefficient \( XL \) curve 102, the efficiency coefficient \( C \) curve 103 and the threshold gain GL curve 101 in the laser mechanism illustrated in FIG. 3 where the active material surrounds the optical fiber. The efficiency coefficient \( C \) curve 103 approaches zero as the frequency increases because the energy is confined within the fiber at high frequencies and the active region is located around the fiber. At cut-off the efficiency coefficient \( C \) curve 103 is close to one because the energy is in the area surrounding the fiber and the active medium is in this area. The threshold gain GL curve 101 illustrates that for the laser structure of FIG. 3, the gain required is relatively smaller at cut-off, probably because the efficiency coefficient is approaching one, and larger at higher frequencies, probably because the efficiency coefficient is approaching zero. The coupling coefficient \( XL \) curve 102, however, is pretty much the same in the structure of FIG. 3 as in the structure of FIG. 2.

FIG. 8 illustrates the relationships of the efficiency coefficient \( XL \) coupling coefficient \( XL \) and threshold gain GL for 0-1 mode coupling in the laser structure shown in FIG. 2. The Y axis 105 represents the coupling coefficient \( XL \) scale. The Y axis 107 represents the efficiency coefficient \( C \) scale. The Y axis 111 represents the threshold gain GL scale. The X axis 109 represents the increasing frequency of the photon energy emitted by the active medium. As can be seen from FIG. 8, the variables, threshold gain, coupling coefficient and efficiency coefficient, for the 0-1 mode behave similar to these variables for the 0-0 mode, illustrated in FIG. 6.

The minimum threshold gain point is the optimum point for design of a laser according to this invention. To illustrate, a specific example will now be given. Consider the case where

\[
\begin{align*}
\delta &= 2a = 0.01 \\
\eta &= 6 \times 10^4 \\
L/a &= 6600, \text{ and} \\
\lambda/a &= 1.2
\end{align*}
\]

For an active material having a wavelength \( \lambda = 1 \mu \)

\[
a = 0.83 \mu
\]

having micromachined grooves, as shown in FIG. 4 to a depth \( d = 0.016 \mu \), a width of 0.5 \( \mu \) with a 0.5 \( \mu \) spacing for an overall length L of 5.5 millimeters. The corresponding threshold gain coefficient is GL=3, which is approaching a total gain of approximately 25 db. This is true for the laser mechanism shown in FIG. 2, having the active medium diffused in the optical fiber. For the laser mechanism shown in FIG. 3, where the active material surrounds the optical fiber, the gain coefficient GL=4.2 which approaches a total gain of approximately 35 db. These gains can be easily achieved with many active materials, such as, neodymium and the organic dyes, for example. It should be also noted that a larger value of \( d/2a \) would lead to an even lower threshold gain.

In summary, what has been described is a way of reducing the signal loss between a laser mechanism and an optical fiber transmission line. This is accomplished by integrating the laser and the optical fiber transmission line through the technique of distributed feedback. It should be understood, of course, that the foregoing disclosure relates only to preferred embodiments of the
invention and that numerous modifications may be made therein without departing from the spirit and the scope of the invention as set forth in the appended claims.

What is claimed is:

1. A laser mechanism comprising:
   an optical fiber having an active material diffused therein;
   pumping means for exciting the atoms in said active material; and
   means for establishing a periodic perturbation in said optical fiber that has a periodicity capable of supporting Bragg reflection.

2. The laser mechanism of claim 1 wherein said establishing means comprises a grating in said optical fiber.

3. The laser mechanism of claim 2 wherein said active material is an organic dye.

4. The laser mechanism of claim 3 wherein said pumping means comprises an optical energy source.

5. The laser mechanism of claim 4 wherein said optical energy source comprises: a high intensity light source spirally wound around said optical fiber.

6. The laser mechanism of claim 2 wherein said active material is neodymium oxide dissolved in selenium oxychloride.

7. The laser mechanism of claim 6 wherein said active material is neodymium oxide dissolved in selenium oxychloride.

8. The laser mechanism of claim 7 wherein said pumping means comprises a high intensity light source spirally wound around said optical fiber.

9. The laser mechanism of claim 2 wherein said grat 
   ing has a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material

10. A laser mechanism comprising:
    an optical fiber immersed in a bath of liquid active material;
    pumping means for exciting the atoms in said active material; and
    means for establishing a periodic perturbation in said bath of liquid active material capable of supporting Bragg reflection.

11. The laser mechanism of claim 10 wherein said establishing means comprises a grating in said optical fiber.

12. The laser mechanism of claim 11 wherein said active material is neodymium oxide dissolved in selenium oxychloride.

13. The laser mechanism of claim 12 wherein said pumping means comprises an optical energy source.

14. The laser mechanism of claim 13 wherein said optical energy source comprises a high intensity light source spirally wound around said bath of liquid active material.

15. The laser mechanism of claim 11 wherein said active material is a fluorescent dye dissolved in a solution.

16. The laser mechanism of claim 15 wherein said pumping means comprises an optical energy source.

17. The laser mechanism of claim 16 wherein said optical energy source comprises a high intensity light source spirally wound around said bath of liquid active material.

18. The laser mechanism of claim 11 wherein said grating has a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material.

19. A laser mechanism comprising:

20. The laser mechanism of claim 19 wherein said establishing means comprises a grating in said optical fiber.

21. The laser mechanism of claim 20 wherein said grating has a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material.

22. A laser mechanism comprising:
    an optical fiber having an active material deposited thereon;
    pumping means for exciting the atoms in said active material; and
    means for establishing a periodic perturbation in said optical fiber that has a periodicity capable of supporting Bragg reflection.

23. The laser mechanism of claim 22 wherein said establishing means comprises a grating in said optical fiber.

24. The laser mechanism of claim 23 wherein said grating has a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material.

25. An optical energy distribution system for transporting energy between point A and point B, comprising:
    an optical fiber extending between point A and point B, said fiber having an active material diffused therein for a short distance at point A and being grated for that distance with a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material; and
    pumping means for exciting the atoms in said active material.

26. The optical energy distribution system of claim 25 wherein said active material is neodymium.

27. The optical energy distribution system of claim 26 wherein said pumping means comprises an optical energy source.

28. The optical energy distribution system of claim 27 wherein said optical source is spirally wound around said optical fiber for the length of grat ing at point A.

29. An optical energy distribution system for transporting energy between point A and point B, comprising:
    an optical fiber extending between point A and point B, said fiber being immersed in a bath of liquid active material for a short distance at point A and being grated for that distance with a periodicity equal to \( N \) times \( \lambda /2 \), where \( N \) is any integer and \( \lambda \) is the wavelength of photons emitted by the active material; and
    pumping means for exciting the atoms in said active material.

30. The optical energy distribution system of claim 29 wherein said active material is neodymium oxide dissolved in selenium oxychloride.

31. The optical energy distribution system of claim 30 wherein said pumping means comprises an optical energy source.
32. The optical energy distribution system of claim 31 wherein said optical energy source comprises a high intensity light source spirally wound around said fiber for the length of grating at point A.

33. An optical energy distribution system for transporting energy between point A and point B, comprising:

an optical fiber extending between point A and point B, said fiber having, an active material deposited thereon for a short distance at point A and being grated for that distance with a periodicity equal to $N \times \frac{\lambda}{2}$, where $N$ is any integer and $\lambda$ is the wavelength of photons emitted by the active material; and

pumping means for exciting the atoms in said active material.

34. The optical energy distribution system of claim 33 wherein said active material is an organic dye.

35. The optical energy distribution system of claim 34 wherein said pumping means comprises an optical energy source.

36. The optical energy distribution system of claim 35 wherein said optical energy source comprises a high intensity light source spirally wound around said optical fiber for the length of grating at point A.