Supermode Si/III-V hybrid lasers, optical amplifiers and modulators: A proposal and analysis

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Abstract: We describe a hybrid laser structure which consists of an amplifying III-V waveguide proximity-coupled to a passive Si waveguide. By operating near the synchronism point (where the phase velocities of the individual waveguides are equal), we can cause the optical power to be confined to any of the two waveguides. This is accomplished by control of waveguides' geometry. In the portion of the supermode resonator where amplification takes place, the mode is confined nearly completely to III-V guide thus realizing a near maximal gain. Near the output facet, the mode power is confined to the Si waveguide thus optimizing the output coupling. This is to be contrasted with approaches which depend on evanescent field penetration into the III-V medium to obtain gain.

OCIS codes: (999.9999) Silicon photonics; (250.3140) Integrated optoelectronic circuits; (130.2790) Guided waves; (130.3120) Integrated optics devices; (140.5960) Semiconductor lasers.

References and links

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1. Introduction

The realization of optical lasers utilizing silicon as the lasing medium remains an elusive holy grail in optical communication research. Some of the approaches described recently employ: (1) Raman oscillation in Si [1], and (2) a hybrid AlGaInAs-Si evanescent laser [2]. In the second approach the available gain is limited due to the reliance on the (weak) evanescent field penetration from the Si waveguide into an amplifying III-V slab. In what follows we propose a new hybrid Si/III-V laser guiding structure which is based on the supermodes of a two (coupled) waveguide systems. This approach eliminates, in principle, the basic compromise inherent in the evanescent laser design since the full modal power, rather than the evanescent tail, is available for amplification. This results in a larger gain and increased efficiency.

2. Supermode Si/III-V hybrid laser

In the proposal and analysis which follow we describe, analyze, and present detailed numerical simulations of a new type of a III-V(AlGaInAs)−Si hybrid laser which we call the "Supermode Si/III-V Hybrid Laser." The name Supermode was coined originally to describe modes of a system of parallel and coupled optical waveguides [3, 4]. Our proposed laser utilizes a system of two such coupled waveguides. The first guide is made of a III-V amplifying material while the second is a silicon waveguide fabricated in the Si substrate. As

#83002 - $15.00 USD Received 11 May 2007; revised 6 Jul 2007; accepted 7 Jul 2007; published 11 Jul 2007

will be discussed further below, it is possible, by a proper choice of the width of the Si waveguide, to direct the modal power to the amplifying III-V waveguide or to the Si waveguide, thereby avoiding the degraded performance which results from the reliance on the evanescent field. The modal power is then diverted to the Si waveguide by adiabatically increasing its width. This makes for efficient coupling to the outside.

3. Supermode theory and supermode control in Si/III-V hybrid laser

The ability to spatially confine the optical power to any one of the two waveguides follows directly from the theory of Supermodes. According to this theory [3], the modes of a system consisting of two coupled waveguides can be obtained by a diagonalization of the more conventional coupled-mode equations used to describe them.

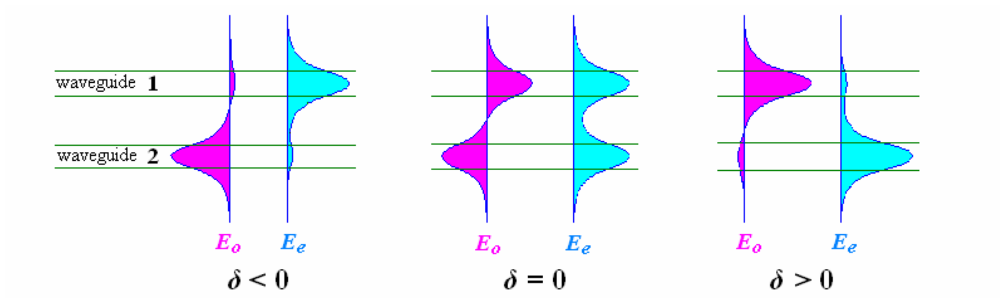

Fig. 1. A schematic representation of the two supermodes E_o and E_e for three values of the mismatch parameter δ.

We refer to Fig. 1 which shows two waveguides **1** and **2** coupled, by proximity, to each other. The transverse (x, y) dependency of the supermode consists of a linear combination of the modes of the separate (uncoupled) waveguides which combination travels with a single phase velocity. It can be written as:

$$E(x,y,z) = \left[au_1(x,y) + bu_2(x,y)\right]e^{-i\beta z}. \tag{1}$$

For a given mode of the individual waveguides there exist two modes of the coupled system, which we designate by the subscripts o and e. Each of these supermodes is determined by the ratio (a/b) and by a propagation constant β. These are given by [3]:

$$E_o(z) = \begin{vmatrix} b \\ a \end{vmatrix}_o e^{-i\beta_o z} = \begin{vmatrix} \dfrac{i\kappa^*}{\delta + S} \\ 1 \end{vmatrix} e^{-i(\bar{\beta} - S)z} \tag{2}$$

$$E_e(z) = \begin{vmatrix} b \\ a \end{vmatrix}_e e^{-i\beta_e z} = \begin{vmatrix} \dfrac{i\kappa^*}{\delta - S} \\ 1 \end{vmatrix} e^{-i(\bar{\beta} + S)z} \tag{3}$$

where

$$2\bar{\beta} = \beta_1 + \beta_2, \quad 2\delta = \beta_2 - \beta_1, \quad S = \sqrt{\delta^2 + \kappa^2}, \tag{4}$$

and κ is given by an overlap integral involving u_1 and u_2, and the index perturbation function.

Of particular interest are the three limiting values: (1) $\delta<0$ while $|\delta|>>|\kappa|$, (2) $\delta=0$, (3) $\delta>0$ and $\delta>>|\kappa|$. The corresponding modes are respectively:

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(1) $\delta<0$ ($\beta_1>\beta_2$), $|\delta|>>|\kappa|$

$$\left|\begin{matrix} b \\ a \end{matrix}\right|_o \rightarrow \left|\begin{matrix} -1 \\ \varepsilon \end{matrix}\right|, \quad \left|\begin{matrix} b \\ a \end{matrix}\right|_e \rightarrow \left|\begin{matrix} \varepsilon \\ 1 \end{matrix}\right| \tag{5}$$

where $\varepsilon = \left|\frac{\kappa}{2\delta}\right| \ll 1$.

(2) $\delta=0$ ($\beta_1=\beta_2$)

$$\left|\begin{matrix} b \\ a \end{matrix}\right|_o \rightarrow \left|\begin{matrix} -1 \\ 1 \end{matrix}\right|, \quad \left|\begin{matrix} b \\ a \end{matrix}\right|_e \rightarrow \left|\begin{matrix} 1 \\ 1 \end{matrix}\right| \tag{6}$$

(3) $\delta>0$ ($\beta_1<\beta_2$), $\delta>>|\kappa|$

$$\left|\begin{matrix} b \\ a \end{matrix}\right|_o \rightarrow \left|\begin{matrix} -\varepsilon \\ 1 \end{matrix}\right|, \quad \left|\begin{matrix} b \\ a \end{matrix}\right|_e \rightarrow \left|\begin{matrix} 1 \\ \varepsilon \end{matrix}\right| \tag{7}$$

where $\varepsilon = \frac{|\kappa|}{2\delta} \ll 1$.

The corresponding mode profiles are sketched in Fig. 1. The subscripts designation "even"(*e*) and "odd"(*o*) is derived from the modal symmetry at the phase-matched, $\delta=0$, condition.

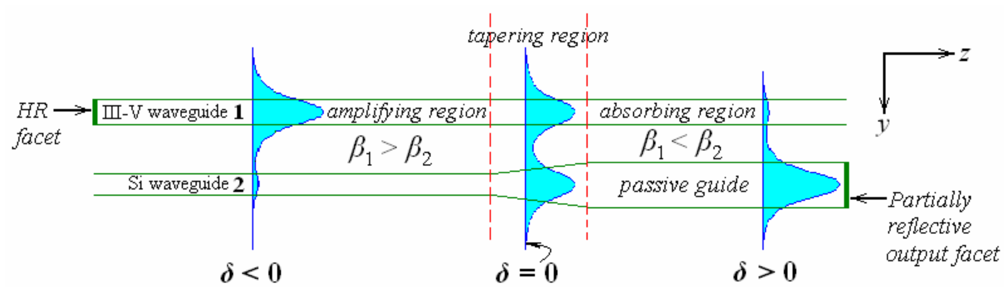

Fig. 2. A schematic representation of the laser structure with one tapered adiabatic transition. See Fig. 3(a) for definition of the directions *x*, *y*, *z* with relation to waveguide geometry.

We are now in a position to understand the basic philosophy of the hybrid Si/III-V laser concept. By controlling the δ parameter, for example by controlling the width of the Si waveguide, we can control in which of the two waveguides the mode power, of either the "*o*" or "*e*" modes, is concentrated. The hybrid supermode laser resonator design is illustrated in Fig. 2. Following the modal field through one round trip, the mode starts propagating from left to right in the upper left III-V waveguide where it is amplified. It then enters the adiabatic transformer section where the width of the Si waveguide increases so as to cause δ to change from $\delta<0$ to $\delta>0$. This causes the modal energy to shift to the lower low-loss Si waveguide where it is partially reflected from the right output facet. The reflected field retraces its path till reflected from the upper left facet thus completing the round trip.

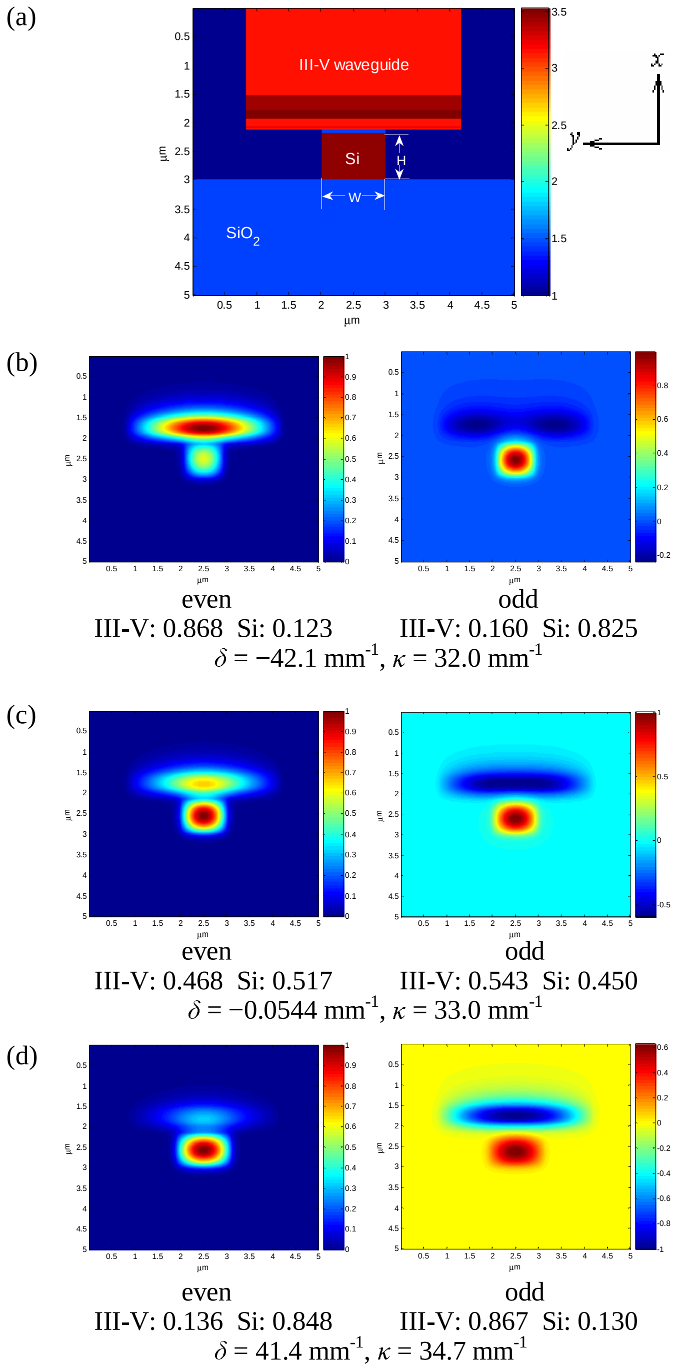

Fig. 3. (a). A cross-section of the Si (bottom) – AlGaInAs (top) structure. The top III-V waveguide mesa width = 3.34 μm. Si waveguide height H = 0.80 μm. (b), (c) and (d) are the optical field profiles (color coded) for the cases δ>0 (W = 0.84 μm), δ=0 (W = 0.99 μm), and δ<0 (W = 1.20 μm), respectively. The fraction of the energy in each waveguide is given at the bottom of each colorgram.

The main advantage of this "spatial switching" of the modal energy is to obtain maximum gain in the inverted medium since the peak modal field and not just an evanescent tail induces the amplifying transitions in the gain (III-V) region. By the same token, essentially the full field is present in the lower right corner of waveguide **2** ready for coupling to other parts of the Si chip or into an output fiber. The odd mode E_o is prevented from lasing since, according to Fig. 1, it would traverse the absorbing (unpumped) right side of waveguide **1** which raises the threshold for this mode. The same principle of spatial switching of the modal power can be used to achieve other functions. For example: To make an optical amplifier, we can switch the input modal power from a wide ($\delta>0$) Si waveguide to a III-V amplifying section ($\delta<0$) and back again to the wide ($\delta>0$) Si waveguide. The same geometry can be used to make an absorption modulator or a current controlled phase or amplitude modulator.

4. Simulation results and discussion

To illustrate the supermodes in the proposed design, we calculated the modal profiles in the coupled waveguide structure using a 2-D modesolver. The III-V waveguide employs an identical layer structure to that used in [2]. The only difference is that we etch a 3.34 μm wide mesa in the center to form a waveguide. Also, we introduce a 0.05 μm thick silica gap between the III-V waveguide and the Si waveguide. The Si waveguide has a fixed height H = 0.8 μm. We vary the Si guide width W to observe the mode evolution at different sections. Fig. 3(a) illustrates the index profile at a cross-section of such a hybrid structure. Figures 3(b), 3(c), and 3(d) show the calculated even and odd supermodes for different Si guide widths. The calculated fraction of energy in each waveguide for each mode, as well as the parameters δ and κ, are indicated at the bottom of each colorgram. We can see, from Fig. 3(c), that when $|\delta|\rightarrow 0$, the energy is divided nearly equally between the two guides. In (b) and (d), the large phase mismatch cases, the modal power is mostly confined to one waveguide, as predicted by the Supermode theory.

To demonstrate the importance of supermode control, we have calculated the confinement factors, for the even mode, in the quantum well region, Γ_{QW}, and in the Si guide, Γ_{Si}, for different Si guide widths. In the evanescent coupling scheme, as mentioned before, there exists a tradeoff between Γ_{QW} and Γ_{Si}. With a fixed Si guide width of 1.10 μm, $\Gamma_{QW} = 0.067$ and $\Gamma_{Si} = 0.757$. In our supermode coupling scheme, if we vary the Si guide width near the output facet from at main body 0.75 μm to at the output facet 1.35 μm, we will have at main body $\Gamma_{QW} = 0.268$, and at the output facet $\Gamma_{Si} = 0.892$. Thus we can increase the Γ_{QW}, hence the exponential gain constant of the laser mode, from 0.067 to 0.268, i.e. a factor of 4×. We also increase the output coupling by, a less impressive, 18%.

5. Conclusion

We propose a supermode hybrid Si/III-V laser design. This approach gets away from the reliance on evanescent tails. Its theoretical foundation is the theory of coupled waveguides, and more specifically, the concept of supermodes – the modes of a system of two or more coupled waveguides. The supermode resonator based on this system can be designed such that the optical energy is confined to either the Si or to the III-V waveguide as desired. This is achieved, most easily, by tailoring the width of one of the waveguides. We can thus use each of the two component waveguides optimally: The III-V guide for gain, the Si waveguide for chip transport and output coupling. This methodology can be extended straightforwardly to hybrid laser amplifiers and to phase or amplitude modulators and thus form the basis of a new hybrid optoelectronic circuitry.

Acknowledgments

The authors acknowledge valuable assistance from Dr. Joyce Poon and Mr. Lin Zhu.