works of any nature. Because no losses are involved in eqn. 1, the device is essentially lossless. Some loss occurs due to manufacturing imperfections: the maxima do not reach unity. For λ below λ_c some deficiency appears due to competition of the next higher-order mode.

With the single-fibre input it is a demultiplexer for the wavelengths 1·08 and 1·38 μm. With the single-fibre output it is a multiplexer when power at 1·08 μm is fed into the coupled port and power at 1·38 μm is fed into the through port. It is therefore also a wavelength-selective lossless splitter/coupler required for two-wavelength full-duplex transmission over a single fibre. Power at 1·38 μm flows over the through ports and power at 1·08 μm over the coupled ports, in both directions. For the wavelengths of 1·21 μm and 1·52 μm the device is a 50/50 splitter/coupler, to be used, for instance, in an interferometric sensor arrangement. At a 20 nm wavelength difference it is a 40/60 splitter/coupler. When two identical FHEs are joined the device is a directional coupler. This four-port application demands much stronger control of the manufacturing reproducibility than the three-port applications mentioned.

Discussion: In systems the applications mentioned above demand that the critical points are located at the desired wavelengths of 1·3 and 1·5 μm. Tailoring the curves of Fig. 1 to this effect requires that the values of d and L which yield the correct values of $K_0 L$ and $K'L$ are computed, and that the etching and fusing processes are controlled carefully enough to achieve these values. For the 50/50 splitter/coupler, at the λ where the two curves cross, the splitting ratio is most λ-dependent. When two different fibres are used so that the depth of modulation $K^2/\beta_0^2 = 0{\cdot}5$ and hence $\beta_1 - \beta_2 = 2K$, then a 50/50 splitter is made at the point of zero slope. With $\beta_1 - \beta_2 = 2\pi\, \Delta n_e/\lambda$, it turns out that this effect can be reached when $\Delta n_e \sim 10^{-4}$, i.e. when the two fibres are only slightly different in a or NA.

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ROLE OF PETERMANN'S *K*-FACTOR IN SEMICONDUCTOR LASER OSCILLATORS—A FURTHER NOTE

Indexing terms: Optics, Semiconductor lasers

The classical Schawlow–Townes formula for the linewidth of a laser should be multiplied by a factor $K' = (1 + \alpha_A^2)K/2$. In this formula, α_A is the ratio of changes in the real and imaginary parts of the complex resonant frequency resulting from a change in carrier density, and K is Petermann's factor. It is shown here that this factor is identical to a result reported in 1971 by other authors in connection with impatt oscillators.

When a laser operates in the unsaturated regime the populations of the upper and lower levels are independent of time. The laser linewidth is then given by the Schawlow–Townes (ST) formula[1] provided the Q-factor of the cold cavity is large, or else provided the laser medium is spatially homogeneous. Otherwise, the ST result must be multiplied by the K-factor introduced by Petermann.[2] A simple expression for K, applicable to any electromagnetic cavity, has been reported in References 3–5.

Usually, lasers operate in the saturated regime, and the laser linewidth is only half that predicted by the ST formula because amplitude fluctuations are suppressed. On the other hand, the linewidth is increased by a factor approximately equal to $1 + \alpha^2$, where α denotes the ratio of changes in the real to imaginary parts of the active medium refractive index caused by carrier fluctuations, as Henry has shown first.[6] (The so-called 'adiabatic' approximation is made throughout this letter. Effects related to relaxation oscillations are not considered.)

Arnaud,[7] however, has shown that the ST result should be multiplied by the more accurate factor

$$K' = (1 + \alpha_A^2)K/2 \tag{1}$$

where α_A is the ratio of the real to imaginary parts of the laser cavity complex resonant frequency caused by a carrier density change. In some circumstances, this factor differs significantly from Henry's α-factor. Furuya[8] introduced earlier a factor α_e, defined as the ratio of changes of the real and imaginary parts of the propagation constant at a fixed real frequency. However, one can show (using the fact that the propagation constant is a regular function of frequency) that α_A coincides with α_e only when the wave gain is independent of frequency. This is not the case in general. Furthermore, the α_e-factor makes sense when the laser cavity incorporates a uniform waveguide section, but not for an arbitrary cavity.

The purpose of this letter is to show that our result in eqn. 1 is in fact identical to a result given in 1971 by Thaler *et al.*[9] in connection with impatt oscillators. The agreement would not be obtained if α_A in eqn. 1 were replaced by α or α_e, or if the K-factor were omitted.

The derivation in Reference 9 is exceedingly simple. The active medium is represented by an admittance $-Y_0(n)$, where n is the carrier density (or any other relevant parameter, such as field strength or temperature), in parallel with a linear admittance $Y(f)$, where f denotes the (real) optical frequency. The frequency dependence of Y_0 is neglected here for simplicity, without much loss of generality.

If there were no noise source the circuit equation

$$Y_0(n_0) - Y(f_0) = 0 \tag{2a}$$

would hold, where n_0 and f_0 are constant carrier density and resonating frequency, respectively. In the following, we set $Y_0 = G_0 + iB_0$ and $Y = G + iB$. The fluctuation-dissipation (or optical Nyquist) theorem, however, tells us that a white Gaussian current source is associated with any active conductance (complete population inversion and zero temperature are assumed, for simplicity). For narrowband operation about the frequency f_0, this noise current can be written as $c(t) + is(t)$, where c and s are white Gaussian uncorrelated processes whose spectral densities are equal to $4hf_0 G_0$. Because of this current source, the circuit equation becomes

$$Y_0(n(t)) - Y(f(t)) = (c(t) + is(t))/V_0 \tag{2b}$$

where the voltage V across the circuit has been replaced on the right hand side of eqn. 2b by its RMS value V_0. In other words, as in Reference 7, we postulate that the voltage fluctuations are suppressed by saturation.

To first order, eqns. 2 give, separating real and imaginary parts,

$$G_{0n}\, \delta n(t) - G_f\, \delta f(t) = c(t)/V_0 \tag{3a}$$

$$B_{0n}\, \delta n(t) - B_f\, \delta f(t) = s(t)/V_0 \tag{3b}$$

where the subscripts n, f denote differentiations with respect to these variables, the resulting quantities being evaluated at n_0, f_0. Also, δn and δf refer to small variations of n and f.

It suffices now to eliminate δn between eqns. 3a and b to obtain the instantaneous laser frequency $\delta f(t)$:

$$\delta f(t) = (V_0 B_f)^{-1}[\alpha c(t) - s(t)]/(1 - \alpha h') \tag{4}$$

where we have introduced Henry's α-factor, $\alpha = B_{0n}/G_{0n}$, and

$$h' \equiv G_f/B_f \tag{5}$$

This h'-factor (denoted by h in Reference 7) is simply related to Petermann's K-factor by $K = 1 + h'^2$, as we shall see later.

The (one-sided) spectral density $S_{\delta f}$ of the $\delta f(t)$ process follows from eqn. 4 and the spectral properties of the $c(t)$ and $s(t)$ processes given earlier. The laser full width half-power (FWHP) linewidth Δf is equal to $\pi S_{\delta f}$. Thus

$$\Delta f = \pi S_{\delta f} = 4\pi h f_0 G_0 (V_0 B_f)^{-2}(1 + \alpha^2)/(1 - \alpha h')^2 \tag{6}$$

This result is essentially that given in 1971 by Thaler *et al.*,[9] except for the introduction of the photon energy hf_0 in place of the thermal energy kT.

We show now that eqns. 1 and 6 are identical. To make this comparison, we introduce the ST expression for the laser linewidth

$$\Delta f_{ST} = 2\pi h f_0 (\Delta f_0)^2/P \tag{7}$$

where

$$\Delta f_0 = -2GB_f(G_f^2 + B_f^2)^{-1} = -2(G/B_f)(1 + h'^2)^{-1} \tag{8}$$

denotes the cold-cavity linewidth, obtained by suppressing the active conductance $-G_0$ from the circuit, and $P = GV_0^2$ denotes the power dissipated in the load conductance G.

We can therefore write eqn. 6 in the form

$$\Delta f = \tfrac{1}{2}\Delta f_{ST}(1 + \alpha^2)(1 + h'^2)^2/(1 - \alpha h')^2 \tag{9}$$

Note that $G_0 \simeq G$ at resonance.

The linewidth enhancement factor in eqn. 9 can be written in the more convenient form of eqn. 1, i.e. $(1 + \alpha_A^2)K/2$, if we use the expression for α_A already given in Reference 7:

$$\alpha_A \equiv \delta f_r/\delta f_i = (\alpha + h')/(1 - \alpha h') \tag{10}$$

and the relation $K = 1 + h'^2$.

We have shown in Reference 7 that every axial mode of a semiconductor laser with a thin active slab can be represented by an electrical circuit like the one discussed in this letter. The thin active slab is represented by a negative admittance $u_0 \equiv b_0 + ia_0$, while the lossy confining layers are represented by an admittance $u(f) \equiv b(f) + ia(f)$. In that special case, $a(f)$ and $b(f)$ have a constant product. It therefore follows that the expression for K given earlier, namely $1 + (G_f/B_f)^2$, gives $K = 1 + (-b/a)^2 \simeq 1 + (b_0/a_0)^2$, which also follows from Petermann's formula.[2]

In conclusion, we have shown that the laser linewidth enhancement fractor reported by us in Reference 7 differs, at least in principle, from previously reported results in the laser field, but is in exact agreement with a result derived much earlier in the microwave field. For usual index-guided lasers, the difference between our eqn. 1 and Henry's $(1 + \alpha^2)/2$ factor is admittedly rather small. However, the difference may be significant for very high-gain lasers, gain-guided lasers and lasers with external reflection.

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VERY LOW-LOSS GaInAs/InP OPTICAL WAVEGUIDES FOR THE 10·6 μm WAVELENGTH

Indexing terms: Integrated optics, Optical waveguides

Optical waveguides for the 10·6 μm wavelength have been fabricated using the MOCVD technique in the InP/GaInAs system. First, the indices of refraction of the relevant materials are determined using integrated-optic techniques. Then, high-optical-quality optical waveguides are reported with propagation losses as low as 0·7 dB/cm. These structures are the basis of more sophisticated electrically controlled devices for 10·6 μm.

Introduction: The recent progress realised in vapour-phase epitaxy with III-V compounds, particularly the development of the MOCVD method, give new possibilities for the investigation of passive and active structures for the 10·6 μm wavelength.

Integrated optics geometry is particularly interesting,[1–3] as it permits low-drive-voltage electro-optic devices, which is an important consideration at this wavelength. The large substrate area processing capability of MOCVD could lead to very efficient devices, especially if the propagation losses are low.

To facilitate the future implementation of *pn* junctions, it is convenient to use a heavily doped substrate. To minimise the losses, it is thus of prime importance to confine the guided light as far as possible from the high carrier concentration substrate, where optical absorption will be unacceptably high in the spectral range we are interested in. As a consequence, it is necessary to use a first film of undoped low-index material to act as a cladding (*n*-InP) and then a high-index undoped film (such as *n*-GaInAs) where the guided mode will propagate. If the cladding layer is thick enough and/or if the refractive index difference between the cladding and the guide is high enough, the losses can be reduced to reasonable values.

In this letter we describe experimental results concerning low-loss planar optical waveguides in the GaInAs/InP system obtained with the low-pressure MOCVD technique.[4]

Experiment: As a first step in being able to define a low-loss structure, it is necessary to know the optical characteristics of the different materials to be used at 10·6 μm.

As the final projected structure is based on the association of n^+-InP (substrate), *n*-InP (cladding) and *n*-GaInAs (waveguide), several test waveguides were grown by MOCVD to include different combinations of materials, to permit refractive index calculations by measuring the propagation constants of the guided modes. More precisely, multimoded planar waveguides were fabricated as follows:

(a) *waveguide 1:* InP (*n*-type: $<10^{15}$, thickness $\simeq 10\,\mu$m)/InP (n^+: 2×10^{18})