The RC^{2}LED: A Novel Resonant-Cavity LED Design Using a Symmetric Resonant Cavity in the Outcoupling Reflector

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***Abstract*—We present the concept of a novel resonant-cavity LED design where a symmetric resonant cavity (RC) is added to the outcoupling reflector. Because of the peculiar characteristics of the resulting mirror, these so-called RC^{2}LED's have a much higher extraction efficiency into a limited NA as compared to conventional RCLED designs.**

***Index Terms*—Light-emitting diodes, microcavity, resonant cavity.**

I. Introduction

RECENTLY, resonant-cavity light-emitting diodes (RCLED's) have attracted considerable interest, mainly because of the possibility of increased extraction efficiency in planar (one-dimensional) cavities as compared to standard LED's [1], [2]. Record extraction efficiencies as high as 22% [3] and even 27% [4] have been reported, but at the expense of wide radiation patterns, making them less suitable for fiber applications.

In the past, efforts have been undertaken to design RCLED's with narrower radiation patterns [5]. This approach normally involves growing an undertuned cavity, i.e., a cavity that is too short as compared to the resonance wavelength. This yields narrower radiation patterns, but at the expense of lower extraction efficiencies, since the microcavity resonance only enhances a limited subset of the spectral and angular spectrum emitted by the active layer.

A possible way to alleviate this problem is the use of reflectors other than the traditional distributed Bragg reflector (DBR) mirrors. Such mirrors should ideally yield a narrower radiation pattern while at the same time enhancing a large fraction of the spontaneous emission. To this end, we propose to add a symmetric resonant cavity (RC) to the outcoupling DBR of the device. When carefully designed, the combination of a DBR and an RC can form a resonant-cavity reflector (RCR) having the following properties.

- The RCR has the same reflection characteristics for resonant normal incidence as the traditional DBR, because the RC is completely transparent under these incidence conditions.

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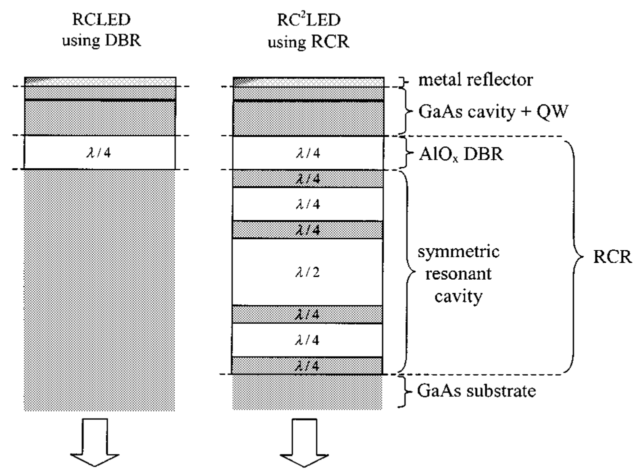

Fig. 1. RCLED versus RC^{2}LED.

- The RCR only transmits light in a narrower cone around normal incidence as compared to the DBR. This leads to a more directional radiation pattern.
- The RCR has a *negative* effective penetration depth (phase-folding behavior). This enhances a larger fraction of the spontaneous emission, by the creation of extra resonances in the extraction cone.
- Using an RCR, TE-leaky modes are significantly suppressed. This eliminates a loss mechanism present in normal RCLED's.

The rest of this paper is organized as follows. In Section II, the characteristics of the RCR are explored. In the next sections, we investigate the effect of using an RCR in an RCLED to form a so-called RC^{2}LED [6]. This is done for a monochromatic emitter in Section III and for the more realistic case of a spectrally broad emitter in Section IV.

II. The Resonant Cavity Reflector (RCR)

To illustrate the concepts of this reflector, we restrict ourselves to the high-contrast AlO_x–GaAs material system, where the effects are the most pronounced. The feasibility of using this system for growing reflectors has been demonstrated many times before [4], [7]. At this time, we only consider incidence at the resonance wavelength. Wavelength-dependent characteristics will be treated in Section IV.

We compare the following bottom-emitting RC devices that differ only in their outcoupling mirrors (Fig. 1). Both devices

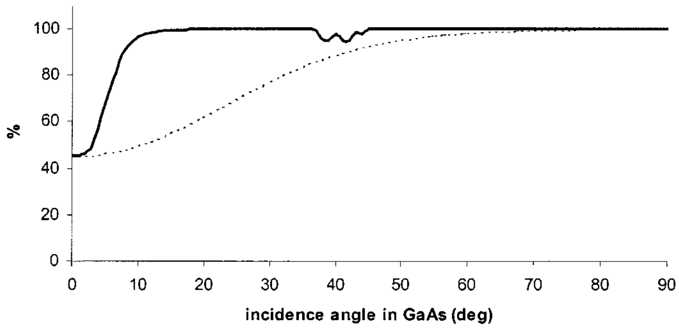

Fig. 2. TE reflectance for a DBR and RCR, as seen from the GaAs cavity (solid line: RCR; dashed line: DBR).

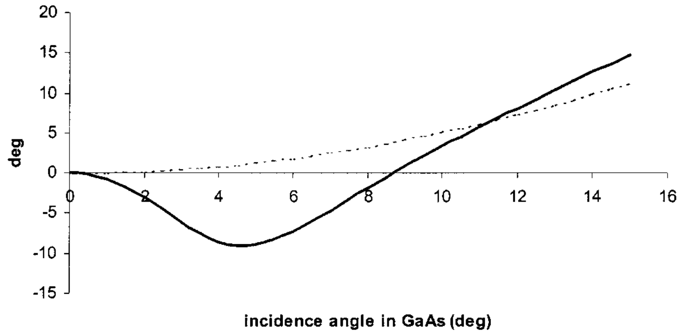

Fig. 3. Phase of TE reflection for a DBR and RCR, as seen from the GaAs cavity (solid line: RCR; dashed line: DBR).

consist of a top metal mirror $(n = 0.2-6.5j)$ doubling as a current contact, a 189-nm GaAs $(n = 3.5)$ RC, and a quantum well (QW) emitting at 980 nm placed at a field maximum. The first device is a traditional RCLED using a single quarter-wave layer AlO_x $(n = 1.55)$ as a DBR. Using extra layers for this mirror would be detrimental for the extraction efficiency, as the normal incidence reflectance would become too high [8]. The second structure, the RC^2LED, has an RCR as the bottom mirror, consisting of the same quarter-wave AlO_x layer, but with an added symmetric $\lambda/2$ RC having the same resonance wavelength. The mirrors of this added cavity are two three-layer GaAs–AlO_x DBR's.

In this section, we compare the reflection characteristics for 980 nm of this DBR and the RCR as seen from the active cavity containing the QW.

First of all, it can be proven with, e.g., transmission matrix theory [9], that the symmetric RC in the RCR is completely transparent for light at normal incidence at the resonance wavelength. This implies that we can design the reflection characteristics for normal incidence independently from those for off-axis incidence. This is important, since one should be able to choose the reflectance for normal incidence low enough in order to design devices with high efficiencies [8].

Secondly, it is well known that the reflection from an RC will always be very high, except when the incident light corresponds to a cavity resonance. Therefore, the combination of a normal DBR with a symmetric RC yields a structure where the reflection for off-axis incidence is always high, while the reflection for normal incidence can be independently controlled. These points are illustrated in Fig. 2, comparing the TE reflectivity of the DBR and the RCR as a function of incidence angle (the TM curves are similar). From this figure, it is obvious that an RC^2LED using an RCR to couple out the light will have a more directive radiation pattern, since the transmission of the RCR is only significant in a much smaller cone as compared to the DBR.

This could lead to the impression that an RC^2LED will also have a significantly lower extraction efficiency, since only a narrow cone of light is coupled to the outside while the rest is effectively thrown away. However, this detrimental effect is largely compensated for by the peculiar phase properties of the RCR. Provided that the symmetric RC has an odd number of high-contrast layers on each side, the RCR has a significant *negative* angular penetration depth (negative phase slope). This is shown in Fig. 3. As we shall see in Section III, these "phase-folding" properties of the RCR result in a much larger cavity enhancement for the narrow light cone escaping the RC^2LED, as compared to the same light cone in the RCLED.

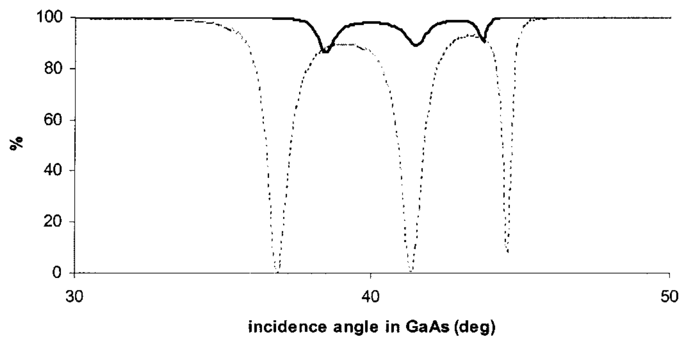

Fig. 4. TE reflectance for a 3.5-pair DBR and an RCR, as seen from the GaAs cavity, showing the suppression of leaky modes (solid line: RCR; dashed line: 3.5-pair AlO_x DBR).

Finally, we point out that such novel reflectors are also useful for suppressing the TE leaky modes. It was already apparent from Fig. 2 that the RCR has a reflectance >90% for incidence angles above 10 degrees, much higher than that of the single-layer DBR. However, the RCR also outperforms a traditional multipair GaAs–AlO_x DBR in this respect. This is shown in Fig. 4, comparing the RCR to a 3.5-pair GaAs–AlO_x DBR. It is clear that a normal DBR has regions in which the reflectivity is close to zero. This is a loss mechanism for the microcavity effect, since light incident under those angles will immediately escape without benefiting from the microcavity interference effects. For the same angles, however, the RCR has a reflectivity higher than 90%. In this way, the extraction efficiency can be enhanced further by the photon recycling effect [4]. Unfortunately, this is only true for TE polarization. In the TM case, the existence of the Brewster angle forces the reflectivity to zero for both the RCR and the DBR.

III. RC^2LED WITH MONOCHROMATIC EMITTER

The effect of using an RCR instead of a DBR in a microcavity LED can be best understood using a graphical representation in the k-vector space [10].

For the sake of clarity, we restrict ourselves in this section to monochromatic emission from the active layer. This emission can be represented by a circle in k-space, since

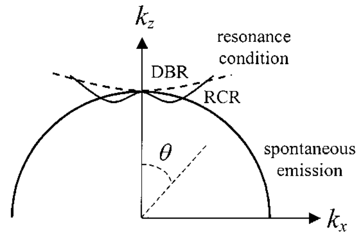

Fig. 5. Schematic k-diagrams for an RCLED and an RC^{2}LED.

every emitted wave has a k-vector with the same length but different orientation.

The phase condition for resonant enhancement by the cavity can be written as ($e^{j\omega t}$ time dependence)

$$\phi_{\mathrm{top}}(\theta) + \phi_{\mathrm{bot}}(\theta) - 2kL\cos(\theta) = l2\pi, \quad \text{with } l \text{ integer.} \tag{1}$$

Here, θ is the incidence angle in the cavity material, ϕ represents the phase of the reflection coefficient of the top or bottom mirror, k is the amplitude of the wavevector in the material, and L is the distance between the two mirrors.

From (1), we can trivially derive the k-vectors that satisfy the resonance condition

$$k_{\mathrm{res}}(\theta) = \frac{\phi_{\mathrm{top}}(\theta) + \phi_{\mathrm{bot}}(\theta) - l2\pi}{2L\cos(\theta)}, \quad \text{with } l \text{ integer.} \tag{2}$$

This equation represents a surface in k-space. k-vectors that lie both on this surface and on the circle representing spontaneous emission correspond to radiation that is strongly enhanced by the cavity. Fig. 5 shows a typical example of such diagrams for an RCLED and an RC^{2}LED.

Both devices have a resonance for normal incidence ($\theta = 0$). The RC^{2}LED, however, has a second intersection between the resonance curve and the emission circle because of the phase-folding behavior of the RCR. This extra off-axis resonance lies within the extraction cone to air and therefore boosts the extraction efficiency.

Diagrams such as Fig. 5 can also be used to explain the effect of changing the cavity length. It can easily be understood from (2) that increasing the cavity length means that the resonance curves will shift downward, while a decrease results in an upward shift. Therefore, increasing the cavity length will cause the side resonances to shift to larger angles, thereby broadening the radiation pattern.

These results are quantified in Fig. 7, showing the calculated percentage η_{NA} of the total extracted power that falls within the NA of the fiber. η_{NA} is shown as a function of the length of the spacer between the QW and the bottom mirror, with the resonance thickness occurring at 140 nm. It is very clear that, in the RC^{2}LED, a significantly higher portion of the extracted light can be coupled into POF. As the cavity length increases, however, η_{NA} decreases because the side lobes shift out of the acceptance cone of the fiber.

A second important performance metric is plotted in Fig. 8, showing the calculated extraction efficiency. The extraction efficiency η_{extr} is defined as the percentage of photons generated in the active layer that is able to escape to air. Antireflection coating was not taken into account, nor was the effect of photon recycling. Both phenomena would lead to a higher efficiency. It is clear that at resonance there is almost no efficiency penalty for the use of an RCR. Not coupling out the light at large off-axis angles is compensated for by the creation of a second resonance within the narrow radiation cone.

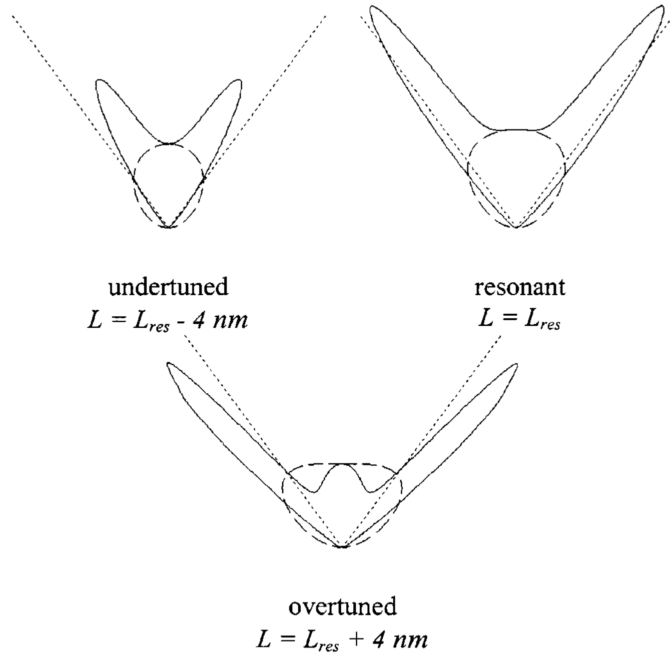

Fig. 6. Influence of cavity length on radiation pattern (full line: RCR, dashed line: DBR).

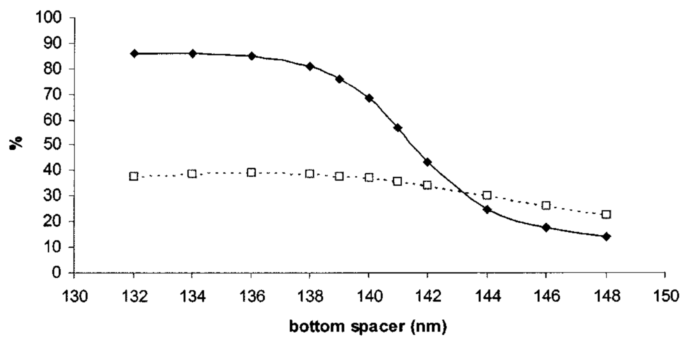

Fig. 7. Power fraction in $\mathrm{NA} = 0.5$ for monochromatic emitter (full line RC^{2}LED, dashed line RCLED).

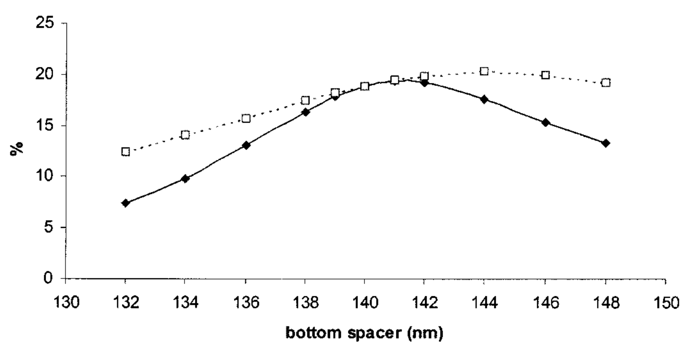

Fig. 8. Extraction efficiency into air (solid line: RC^{2}LED; dashed line: RCLED).

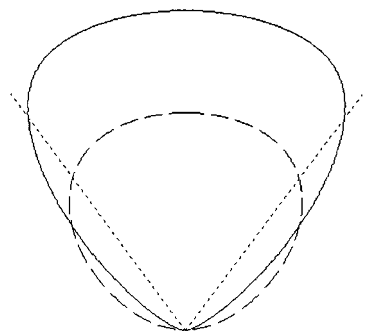

Fig. 9. Radiation patterns for a 45-nm spectral width (solid line: RCR; dashed line: DBR).

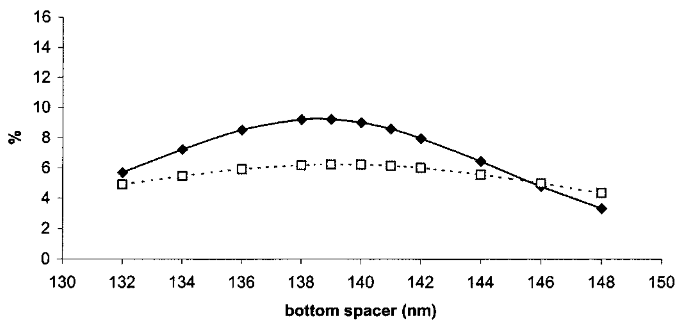

Fig. 10. Extraction efficiency into $\mathrm{NA} = 0.5$ (solid line: RCR; dashed line: DBR).

However, for practical purposes, the relevant figure of merit is $\eta_{\mathrm{extr-NA}} = \eta_{\mathrm{extr}} \cdot \eta_{\mathrm{NA}}$, the percentage of photons generated in the active layer that is able to reach the outside within the acceptance cone of the POF. For the RCLED, this percentage equals 7.0%, while the RC^{2}LED arrives at 12.8%. For comparison, an ideal planar LED without a resonant cavity would only yield 0.5%.These results are confirmed by optical simulations using the model from [8] and [11], as can been seen from the calculated radiation patterns for parallel dipoles in Fig. 6. The same material parameters and wavelengths as in Section II were used. For normal incidence, the radiation intensity is the same for the two devices. The RC^{2}LED, however, exhibits an extra lobe in the radiation pattern. The straight dashed lines in Fig. 6 represent the numerical aperture $\mathrm{NA} = 0.5$ of a plastic optical fiber (POF). It is very clear that, for a correctly tuned RC ^{2}LED, a larger fraction of the emitted light will be coupled to the fiber.

IV. RC^{2}LED WITH A SPECTRALLY BROAD EMITTER

Real active layers such as QW's do not exhibit monochromatic emission, but show a broad spontaneous emission spectrum. Therefore, every wavelength has a slightly different resonance condition [see (2)], since the phase of the mirrors is a function of the wavelength. This also means that every wavelength will have a side lobe at a slightly different angle. All these side lobes combine to form a single-lobed radiation pattern, as shown in Fig. 9, where a Gaussian spontaneous emission spectrum with a FWHM of 45 nm was assumed, again centered at 980 nm.

Still, the RC^{2}LED has a much larger value of η_{NA} (52%) as compared to the RCLED (34%). The extraction efficiency η_{extr} is slightly lower for the RC^{2}LED (17.3% instead of 18.3%). This means that, even with a spectrally broad active region, the RC^{2}LED has much higher values of $\eta_{\mathrm{extr \cdot NA}}$ (Fig. 10).

Finally, it is interesting to note that the phase-folding properties of the RCR also hold in the wavelength domain. This is shown in Fig. 11, plotting the phase of the TE reflection for normal incidence as a function of wavelength. This creates the possibility of having extra side resonances at normal incidence, apart from the one at the design wavelength, once again boosting the efficiency. This is illustrated in Fig. 12(a) and (b), showing the emitted optical spectrum for $\theta = 0$ and $\theta = 30$ degrees.

Note that, for the RC^{2}LED at $\theta = 0$, the resonance peak at 980 nm is hidden by the larger side resonances. Moving to larger angles, the phase characteristics of the mirror shift, resulting in a shift in resonance peaks and resonant intensity. Also note that, although the spectrum at normal incidence has the same signature as a Rabi splitting, it is caused by a different phenomenon, namely the existence of two different resonant optical modes.

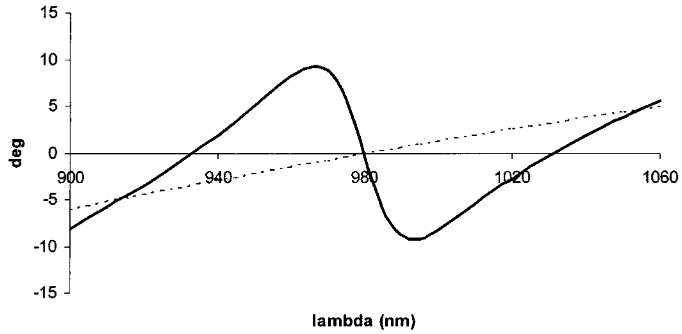

Fig. 11. Phase of TE reflection as a function of wavelength for normal incidence (solid line: RCR; dashed line: DBR).

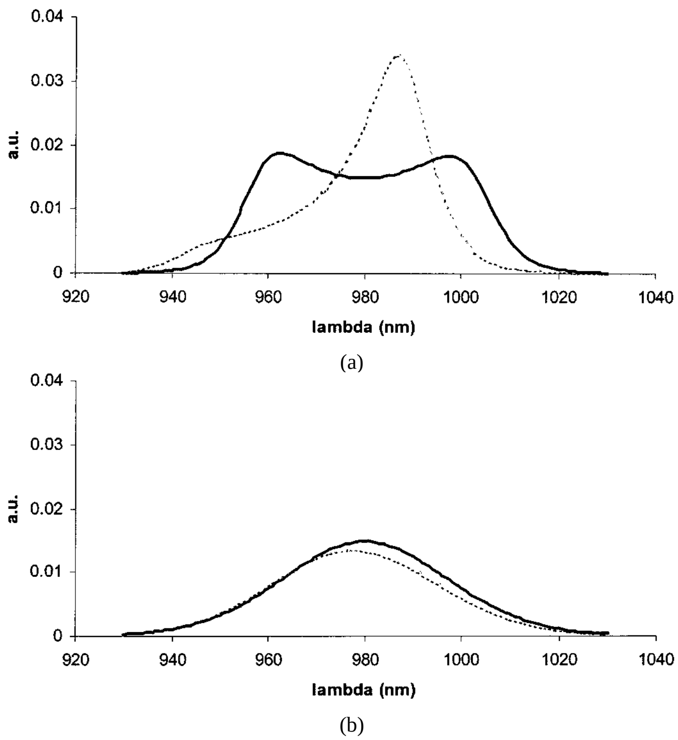

Fig. 12. (a) Emitted optical RC^{2}LED spectrum and (b) emitted optical RCLED spectrum for $\theta = 0$ (solid line) and $\theta = 30$ deg (dashed line).

V. Conclusions

We presented the concept of a novel RCLED design employing a symmetric resonant cavity in the outcoupling mirror. This yields a high reflectance for off-angle incidence with an arbitrary normal incidence reflectance, resulting in a narrower radiation pattern. Also, because of the phase-folding properties of this reflector, extra resonances are created within the extraction cone, boosting the extraction efficiency. This so-called RC^{2}LED design results in devices with much higher extraction efficiencies into a limited NA as compared to conventional RCLED designs. Current research focuses on experimentally realizing these structures.

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