

# RCLEDs for MOST and IDB 1394 Automotive Applications

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**Abstract:** This paper describes the recent progress being made in developing high specification 650 nm resonant cavity light emitting diodes (RCLEDs) for use with plastic optical fibre (POF) in automotive applications. In particular the paper describes the improvements in the high-temperature and high-speed performance of RCLEDs for IDB 1394 and MOST fibre optic transceivers (FOTs) and how RCLEDs are an enabling technology for automotive POF based buses.

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## 1. Introduction

Plastic optical fibre (POF) has for many years been extensively used in industrial field buses such as PROFIBUS, SERCOS and INTERBUS-S for controlling process equipment in rugged manufacturing environments. POF is attractive to the automotive industry because it reduces the weight of the wiring harness and because it provides a very good price-to-performance ratio for multimedia applications due to the availability of low cost connectors and transceivers [1]. In 1998 the digital domestic bus (D<sup>2</sup>B) was introduced in Daimler-Benz cars as the first optical data bus for an infotainment system [1]. The D<sup>2</sup>B bus is based on a ring-bus topology with 1-mm POF and red light-emitting diodes (LEDs) around 650 nm. The system data rate at 5.6 Mb/s is capable of transmitting speech, audio, and control data for phones, sound systems and speech-recognition systems. In 2001 the byteflight [2] POF bus was introduced by BMW into the 7 Series for an airbag sensor and deployment network capable of operating at 10 Mbps. Byteflight is a star net configuration and communication is bidirectional on a single plastic optical fibre. The optical components are composed of a red LED and photodiode integrated into the optical connector. Another milestone for POF based automotive networks also occurred in 2001 with the first use of the media oriented systems transport (MOST) [3] POF based multimedia bus also in the BMW 7 Series. The MOST bus is based largely on the same physical layer as the D<sup>2</sup>B network but with a raw data rate of 44.2 Mbps which allows the transmission of compressed video data. The MOST bus has now been introduced in more than 30 series car models. Now in development is a POF multimedia automotive bus, IDB-1394 [4], based on the consumer IEEE 1394.b standard. This bus is being designed to carry 250 Mbps of data over POF and leverages the IEEE 1394.b bus both in terms of cost and also the availability of PHY and LINK Layer silicon ICs and the future deployment of consumer IEEE 1394 POF products and applications.

A consequence of using standard polymethyl

methacrylate (PMMA) POF is that the light sources must operate in the region of 630 to 685 nm where the attenuation of the fibre is at its lowest. (From 0.14 to 0.4 dB/m depending upon the wavelength). For D<sup>2</sup>B, byteflight and MOST with baud rates less than 50 Mbps conventional red LEDs have been used as shown in Fig.1. LEDs are attractive for two reasons, firstly they have good thermal stability whereby the power variation between -40°C and 85°C is of the order of only -2 dB and secondly LEDs have no threshold behaviour in their current-voltage (I-V) characteristic allowing the use of simple drive circuits. However the challenge with the advent of the higher speed 250 Mbps IDB 1394 bus and a planned second generation MOST bus operating at 155 Mbps is to develop a red light source that can not only meet the higher bandwidth requirements but also meet the severe operating temperature (-40°C to 95°C) and environmental conditions of these automotive specifications.

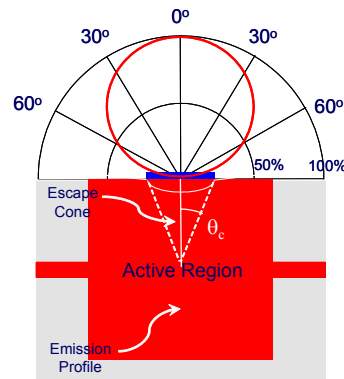


FIG. 1 Schematic representation of a conventional LED showing isotropic mode distribution and subsequent Lambertian radiation pattern in a polar plot.

The maximum bandwidth of the conventional surface emitting LED type structures used in MOST fibre optic transceivers (FOTs) is in the region of 50 Mbps and is then only achieved by the additional use of specially designed peaking circuits. Another feature of these LEDs is their poor external quantum efficiency ( $\eta_{ext}$ ) due in most part to the process of total internal reflection within the LED which prevents the majority

of photons escaping from the LED and leads to an extraction efficiency ( $\eta_{\text{extr}}$ ) of less than 4%. The problem is then further compounded by the relatively low coupling efficiency of the LED's Lambertian radiation pattern into the POF, particularly if no lens is used in the FOT.

Edge emitting lasers are an alternative source with excellent bandwidth properties but their poor thermal behaviour and threshold current characteristic make them an awkward and costly device to control compared to the simpler, reliable and more temperature stable LED.

The resonant cavity light emitting diode (RCLED) on the other hand is a device structure first proposed in 1992 [5] that addresses the fundamental issue of an LEDs low  $\eta_{\text{ext}}$  while providing enhanced spectral and modulation behaviour compared to conventional LEDs. Since 1992 a significant research effort has been expended in developing visible RCLEDs and in particular a record 10.2% wall plug efficiency ( $\eta_{\text{wp}}$ ) was reported by Wirth et al [6, 7], which indicated that these RCLEDs had reached a level of maturity that would enable them to be used in POF applications. Indeed such visible RCLEDs have subsequently become commercially available from companies such as Zarlink and Firecomms. This paper however describes how these RCLEDs have been further refined for use for the first time in automotive applications.

## 2. Resonant Cavity Light Emitting Diodes

A RCLED, as shown in Fig.2, is formed by a thin quantum well active region sandwiched by two mirrors that form a Fabry-Perot cavity. The total active region thickness is an integer number of half wavelengths of the emission wavelength and is thus only a few nanometres thick. The mirrors of the Fabry-Perot resonator can be formed from either a metal or a semiconductor distributed Bragg reflector (DBR). Within such an LED the spontaneous emission from the quantum wells ceases to be isotropic but instead the RCLED cavity promotes emission into resonant modes supported by the cavity while emission into off-resonance modes is suppressed. This cavity effect then produces a profound influence upon the far-field of the device and depending upon the exact design of the device, gives a significant increase in  $\eta_{\text{ext}}$ ; RCLEDs operating at 980 nm have demonstrated  $\eta_{\text{ext}}$  as high as 23% [8].

It is the also the case that RCLEDs display an enhanced bandwidth compared to more conventional LEDs. In general however this behaviour is not due to any related cavity effect but can be attributed to the use of small quantum well active regions and the use of current confining oxide apertures. The use of oxide

apertures both reduces the optical loss from below the contacts and helps maintain a higher carrier density for a given current which leads to a reduction in the spontaneous life-time and hence an increase in the device bandwidth. It is the case therefore that the bandwidth of a RCLED is current dependent. For a detailed examination of the issues governing RCLEDs the reader is referred to a review of RCLEDs by Delbecke *et al* [9].

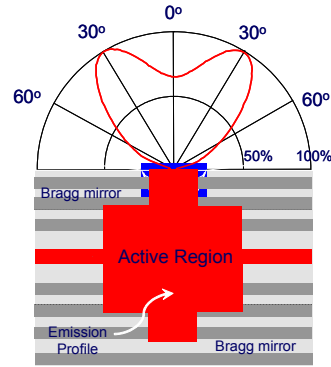


FIG. 2 Schematic representation of a RCLED showing anisotropic mode distribution and subsequent 'rabbit's ears' radiation pattern in a polar plot.

## 3. RCLEDs For Automotive Applications

TABLE I shows a comparison of the emitter (Tx) FOT specifications for the latest revisions of the MOST and IDB 1394 standards. These specifications must be met and maintained over the full operating temperature range,  $-40^{\circ}\text{C}$  to  $95^{\circ}\text{C}$  in the case of MOST, and over the full life-time of the product. For MOST the life-time and reliability of the Tx FOTs is demonstrated by putting the FOT through a well defined and rigorous set of environmental tests including 1000's of hours of active testing at the extremes of operating temperature and humidity. For RCLEDs to form the basis of MOST and future IDB 1394 automotive FOTs, the key features that RCLEDs must demonstrate are (a) high average output power maintained over temperature ( $> -7$  dBm), (b) short rise and fall times ( $< 2$  ns) and (c) high reliability.

Item	Symbol	Unit	MOST 1.1		IDB 1394	
			Min	Max	Min	Max
Baud Rate		MB/s		44.2		250
Peak Wavelength	$\lambda$	nm	630	685	630	670
FWHM	$\Delta\lambda$	nm		30		40
Optical Launch Power	$P_{\text{opt}}$	dBm	-10	-1.5	-7	0
Optical Power Off	$P_{\text{off}}$	dBm		-50		
Extinction Ratio	$r_e$	DB	10		10	
Rise Time (20% - 80%)	$t_r$	Ns		5.97		2
Fall time (80% - 20%)	$t_f$	Ns		5.97		2
Positive Overshoot		%		35		25

TABLE I. A comparison of Tx FOT specifications for MOST and IDB 1394

The conventional types of red LEDs provide a relatively low average output power albeit stable over temperature. For the LEDs used in current MOST transceivers the output power changes at the rate of  $-0.016 \text{ dBm}/^\circ\text{C}$  generating a little over 2 dB drop in power between  $-40^\circ\text{C}$  and  $95^\circ\text{C}$  and is caused by the temperature variation in the internal quantum efficiency of the active region. This temperature dependence of the spontaneous emission also occurs in the RCLED, however, its temperature behaviour is additionally effected by the thermal dependence of the cavity resonance which, in turn, determines the temperature behaviour of the extraction efficiency of the device. The combination of these factors can lead to a large and non-linear temperature sensitivity compared to more conventional designs of planar LEDs. However by undertaking a careful and optimised design of the RCLED active region and optical cavity a highly stable output power can be achieved in a RCLED, particularly at lower drive currents as shown in Fig.3.

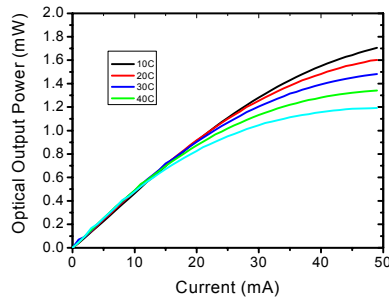


FIG. 3 DC L-I characteristic of a bare die 650 nm Firecomms automotive grade RCLED as a function of temperature, measured using a large area detector.

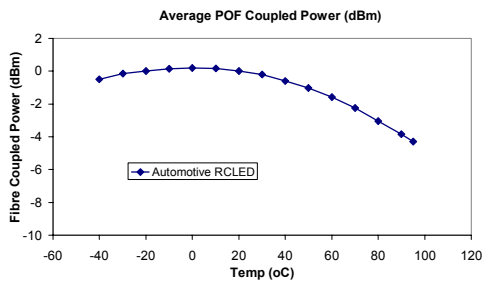


FIG. 4 Fibre-coupled (NA 0.5) average optical power over the temperature range  $-40^\circ\text{C}$  to  $95^\circ\text{C}$  of an automotive grade 650 nm RCLED FOT operated at 250 Mbps with a PRBS 7 bit pattern.

The critical parameter for a POF application is the fibre coupled power. In an automotive FOT the RCLED must be mounted on a lead frame and plastic encapsulated. An enhancement of the fibre coupled power is then achieved through the higher refractive index of the plastic and an optimised design of a coupling lens implemented as part of the moulding process of the FOT. FIG. 4 shows the fibre-coupled

average optical power over the temperature range  $-40^\circ\text{C}$  to  $95^\circ\text{C}$  of an automotive grade 650 nm RCLED FOT operated at 250 Mbps with a PRBS 7 bit pattern. As FIG.4 clearly shows the temperature behaviour of the average power is non-linear, however, the total change in output power over this temperature range is only 4 dB and the power still remains above  $-5 \text{ dBm}$ .

One of the principle reasons to migrate to a RCLED technology is to achieve the necessary bandwidth needed for IDB 1394 buses. As shown in FIG. 5 the automotive grade RCLED (same device as shown in FIG. 4) demonstrates the high speed performance that makes it ideal for IDB 1394 applications.

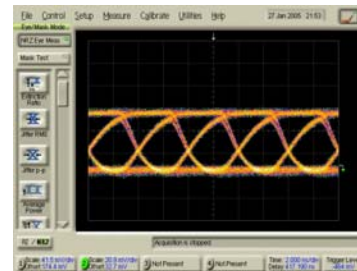


FIG. 5 Shows the clear and open optical eye diagram of the 650 nm RCLED FOT operated at  $-40^\circ\text{C}$  and 250 Mbps with a PRBS 7 bit pattern.

The other critical characteristic that these RCLEDs must display is reliability. Firecomms has collected over 500,000 device hours of reliability data in which the RCLEDs have been run both DC and AC at ambient temperatures of  $-40^\circ\text{C}$ ,  $85^\circ\text{C}$ ,  $95^\circ\text{C}$ ,  $110^\circ\text{C}$  and  $140^\circ\text{C}$  both in plastic FOT packages and on TO style headers. No device failures have been recorded whereby a failure is defined to be a device whose output power had dropped by more than 2 dB. This data shows that RCLEDs show the same high reliability as their more conventional LED relations.

#### 4. RCLEDs FOTs for IDB 1394 Applications

The IDB 1394 specification is a joint development between the IDB Forum [4] and the Automotive Working Group (AuWG) of the 1394 Trade Association [10] and is based upon the IEEE 1394.b specification for S200 (250 Mbps) operation over POF. In June of 2004 the IDB Forum ratified the "PMD for wake-up on LAN" Document (004-005). This was an important step in the development of the IDB 1394 specification as it defined both the physical dimensions and pin-out function of the 5 pin POF FOTs and the wake/sleep functionality needed for power management in automotive applications. A particularly attractive feature of the design is that, in addition to being compatible with the IDB connector, the FOTs are also form factor compatible with the SMI POF connector. Fully integrated IDB 1394 FOTs

conforming to new IDB PMD wake-up on LAN specification are not yet available. However, Firecomms have released 250 Mbps analogue FOT components that do meet the new IDB form factor though external driver and receiver IC's are still needed to implement a digital transceiver. These Firecomms analogue RCLED FOTs were subsequently used in Renault's S200 demonstration of IDB 1394 connectivity in an Espace people carrier, which was able to show features such as picture-in-picture, reversing camera, and i-POD connection to the customer convenience port.

### 5. RCLEDs for MOST Applications

Since the MOST standard currently requires a maximum baud rate of 50 Mbps it may seem unnecessary that RCLEDs should be considered as a device for a MOST FOT. However, there are two compelling reasons as to why RCLEDs should be used. The first is that the automotive RCLEDs described in the previous sections show both high fibre coupled power and good temperature stability and can provide a significant increase in the launched optical power compared to current MOST optical budget. The second significant advantage is that the RCLED technology provides an evolutionary road map for MOST to achieve 155 Mbps over POF.

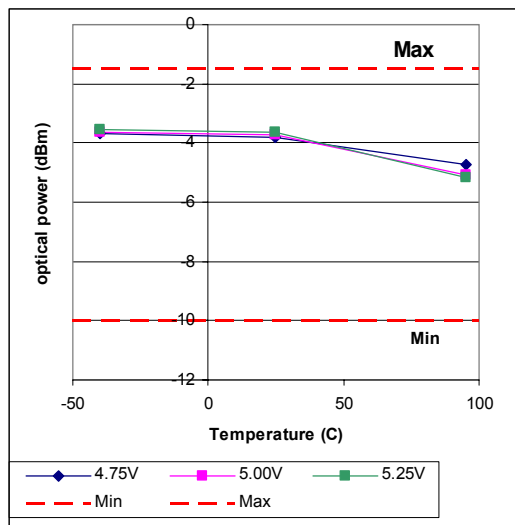


FIG. 6 Shows the average fibre coupled optical power of the Firecomms RCLED MOST Tx FOT measured over temperature and operating voltage. The max and min values of the MOST 1.1 specification are also shown.

Firecomms has developed, as shown in FIG. 6, a Tx MOST FOT using its RCLED technology. Through the optimised design of the RCLED and associated driver IC the MOST FOTs are able to achieve a minimum fibre coupled output power over temperature and aging of -7 dBm, an improvement of 3 dB over the MOST 1.1 specification. In addition the change in

output power over temperature is as low as 2 dB. An additional advantage of the RCLED is that the full width half maximum (FWHM) of the emission remains below 30 nm across the entire temperature range which helps reduce the absorption loss within the fibre.

Firecomms has also developed a corresponding receiver (Rx) FOT that shows an excellent sensitivity of -28 dBm achieved over operating temperature and aging, representing an improvement of 5 dB over the MOST standard requirement of -23 dBm. The combination of the RCLED MOST Tx FOT and the improved sensitivity Rx FOT provide an additional 8 dB of margin to the MOST specification. This margin allows for either an increased number of in-line connectors in the harness or the toleration of higher bend losses in the fibre both of which lead to greater flexibility in the harness design.

### 6. Conclusions

It is clear that the significant developments have occurred in the design of RCLEDs that now enables them to meet rigorous automotive specifications. The realisation of high-speed, high-operating temperature RCLEDs is an enabling technology in developing higher speed and more efficient automotive POF buses.

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