ADVANCED EMITTERS FOR PLASTIC OPTICAL FIBRE

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Abstract: *This paper describes some of the recent progress being made in developing high specification emitters for use with PMMA based plastic optical fibre (POF). In particular the paper describes the developments in 650 nm resonant cavity light emitting diodes (RCLEDs), vertical cavity surface emitting lasers (VCSELs) and high speed LEDs operating at 520 nm. The paper suggests that various POF applications will benefit from the future availability of such sources.*

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. In recent years POF has also begun to be deployed in automobiles using the MOST multi-media bus [1], and Byteflight safety bus [2], developed by the German car industry and which will now compete with the new and faster POF based IDB-1394 multi-media bus [3], also designed for automobile use. The very recent adoption of POF by the IEEE 1394.b standard [4], is opening up further opportunities for using POF in more consumer related applications such as home-theatre and home networking applications. POF is also being applied to back-plane applications while research is now on-going using POF as a physical layer for interconnect between IC's [5].

Although the common physical medium in all these applications is polymethyl methacrylate (PMMA) POF, the specifications for these applications differ significantly in terms of bandwidth, link length, bend loss and operating temperature range. In the case of industrial field buses the impetus is moving towards achieving moderate bandwidths (100 Mbps) over links of at least 100 m across an industrial temperature range of -40^{o}C to 85^{o}C. For automotive applications the trend will be for increased data rates (400 Mbps to 800 Mbps) over shorter link lengths (18 m) with low bend losses but ideally across an enhanced temperature range of -40^{o}C to +125^{o}C. For consumer applications the desire is to achieve high bandwidths (200 Mbps to 400 Mbps) over 100 m, albeit at a less harsh temperature specification of 0^{o}C to 60^{o}C. For back-plane applications the link lengths are very short but the data rates sought are of the order 2.5 Gbps.

It is clear from these trends that the components of the physical layer; the transmitters, receivers and even the POF itself will differ significantly depending upon the application. This paper specifically addresses some of the recent advances being made in the development of advanced optical sources needed to meet these future specifications. In particular the paper describes the current status of Resonant Cavity Light Emitting Diodes (RCLEDs), both red and green, and Vertical Cavity Surface Emitting Lasers (VCSELs) operating in the visible.

2. Resonant Cavity Light Emitting Diodes

For many years the most significant application for data communication grade POF was in the industrial field buses which in general operate at data rates of 2 Mbps and employ planar light emitting diodes (LEDs) with emission at 650 nm. A feature of these LEDs, as with all LEDs prior to the nineties, is their low speed and poor external quantum efficiency (η_{ext}) due in most part to an extraction efficiency (η_{extr}) of less than 4% caused by total internal reflection within the LED. Edge emitting lasers are an alternative source with excellent bandwidth properties but their poor thermal behaviour and threshold current characteristic make them awkward and costly device to control compared to the simpler, reliable and more temperature stable LED. The RCLED however is a device structure proposed in the early nineties that addresses the fundamental issue of the LEDs low η_{ext} while providing enhanced spectral and modulation behaviour compared to conventional planar LEDs [6].

A RCLED 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 nanometers 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 resonances supported by the cavity while off-resonance emission 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 η_{ext}; RCLEDs operating at 980 nm have demonstrated η_{ext} as high as 23% [7].

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 a RCLED's bandwidth is current dependent. For a detailed examination of the issues governing RCLEDs the reader is referred to a review of RCLEDs by Delbeke *et al* [8].

3. 650nm RCLEDs

High quality RCLEDs operating at 650 nm have been demonstrated by a number of groups [9,10] while Pessa et al have recently published a review of these devices [11]. Indeed RCLEDs operating at 650 nm seem to be the most commercially promising RCLED with a number of companies now offering 650 nm products including; Zarlink, Osram Opto, Memscap, and Firecomms. These devices are invariably targeted at IEEE 1394.b applications where high speed (250 Mbaud/s) operation is required.

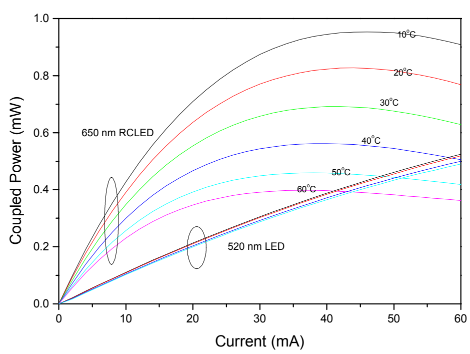

FIG. 1 Comparison of the thermal behaviour of 650 nm RCLED and 520 nm LED fibre coupled power.

It is interesting to compare RCLEDs with more conventional devices such as the HFBR 15X5X series of transmitters from Agilent which are often used in field bus applications. The Agilent transmitters use planar 650 nm LEDs in a plastic encapsulated package designed with a micro-lens for improved coupling into POF with a numerical aperture (NA) of 0.5. At room temperature and a drive current of 60 mA the coupled power into the fibre is -4dBm while the 10%-90% rise/fall time (τ_r) is as long as 13 ns. Fig. 1 shows the light output versus current for a 90 μm aperture RCLED being developed by Firecomms Ltd under the European IST-2000-28234 HOME-PLANET project. The RCLED is packaged in a similar style of package as used by the Agilent component. At room temperature and drive current of 20 mA the coupled power is -2.2 dBm, a significantly higher coupled power achieved at a greatly reduced drive current. The other significant improvement the RCLED delivers is one of bandwidth. The devices of Fig.1 have a measured τ_r of less than 4 ns. Indeed with the use of smaller apertures and peaking circuits data transmission rates of over 600 Mbps albeit over 1 m of POF [11] have been demonstarted.

For a conventional red LED the output power is quite temperature sensitive (-0.02 dB/^{o}C) due to the poor carrier confinement within 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 detuning between the cavity resonance which in turn determines the temperature behaviour of the extraction efficiency of the device. The combination of these factors leads to a large and non-linear temperature sensitivity compared to more conventional designs of planar LEDs. Despite this more complex temperature dependence it is clear that efficient and high speed RCLEDs operating at 650 nm are highly attractive sources for use applications such as IEEE 1394.b. In future such sources may also be capable of meeting a 500 Mbaud/s specification needed for S400.

4. 650 nm VCSELs

In many respects the ultimate source for POF as with any fibre is a VCSEL. VCSELs are characterised by low divergent, circular beam patterns ideal for efficient butt coupling to fibre, exceedingly low threshold currents (a few mA's) and high bandwidth (several Ghz). Electrically pumped nitride VCSELs have yet to be reallised and its likely that the first nitride VCSELs will operate at the blue end of the spectrum rather than the more challenging green. A number of groups however have demonstrated red emitting VCSELs based on AlGaInP and a number of companies including Memscap and Firecomms are in the process of commercialising these devices.

Red VCSELs have a similar epitaixial structure to that of a RCLED although the number of mirror pairs in the top DBR mirror is significantly higher to reach the necessary reflectivities needed in a laser. As with the RCLED the more complex VCSEL structure also suffers from a poor thermal stability which is exacerbated as the operation wavelength approaches 650 nm. This is in most part due to combination of poor carrier confinement, Ohmic heating and absorption in the p-type DBR.

Nevertheless significant progress in the operating characteristics of red VCSELs continues to be reported. Calvert et al [12], recently reported the continuous wave (CW) operation of 670 nm single spatial mode devices to a heat sink temperature of 80^{o}C, while Kinigge et al [13], report 650 nm VCSELs achieving output powers of 3.1 mW at room temperature and 657 nm devices operating to temperatures of 60^{o}C. These results are highly encouraging and suggest that manufacture of 650 nm VCSELs capable of operating up to 70^{o}C is a realistic possibility in near distant future.

5. 520 nm LEDs

A close inspection of the attenuation spectrum of PMMA POF shows that in addition to the narrow optical window at 650 nm (180 dB/km) there are also broader and in general lower attenuation windows (less than 100 dB/km) at 570 nm (amber) and 520 nm (green). The 650 nm window became the de facto standard as this was until recently the POF window at which reasonably efficient LEDs were available. However with the advent of efficient gallium nitride/ gallium indium nitride (GaN/InGaN) LEDs [14], these shorter wavelength windows have become accessible, particularly the 520 nm window where high quality LEDs are available.

The advantages of operating a POF link at 520 nm have been previously described by Ziemann and Krauser [15]. In addition to operating at a lower and broader attenuation window than that at 650 nm these nitride devices provide a significant improvement in the thermal stability of both the output power and emission wavelength. Indeed, the shape of the LEDs spectrum is virtually independent of temperature. These factors combine to enable a greater proportion of the optical budget to compensate for attenuation in the fibre and hence allow fibre links in excess of 100 m to be achieved.

Fig.1 shows the coupled optical power into a 1mm step-index POF (NA=0.5) as a function of temperature for a 520 nm LED of conventional design and a 90 μm aperture 650 nm RCLED fabricated by Firecomms Ltd. In both cases the device die have been packaged in a polymer package that includes a micro-lens to improve the coupling efficiency. Although the RCLED has a significantly higher slope efficiency than the green LED, the temperature dependence of the green LED is clearly lower than the RCLED. At a drive current of 30 mA the drop in fibre coupled power between 10^{o}C and 50^{o}C is -2.9 dB for the RCLED while for the green LED this value is only -0.23 dB.

Green LEDs conventionally used for display applications have also been used to demonstrate the benefits of these nitride devices [16], but due to their long recombination life-time and poor coupling efficiency only a moderate 30 Mbps over 100 m of SI-POF was demonstrated. A European Commission funded consortium [IST-1999-10292: AGETHA], however, are developing sophisticated green nitride LED devices that will in addition to the excellent thermal behaviour of nitride LEDs also deliver improved bandwidth and ultimately improved coupling efficiency and spectral characteristics [17].

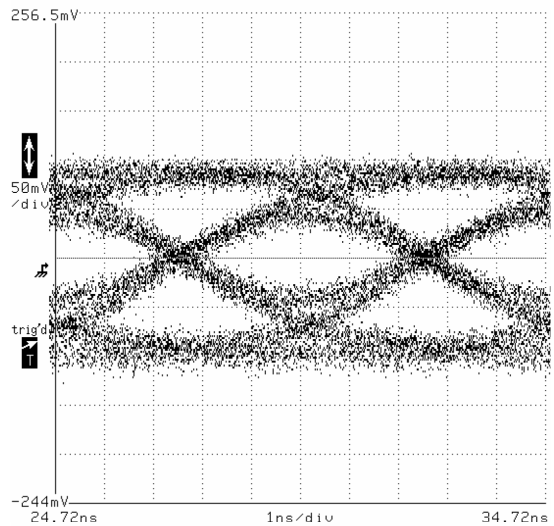

FIG. 2 Eye diagram fro data transmission at 200 Mbps over 100 m of standard low NA (0.3) plastic optical fibre.

The AGETHA consortium has recently reported significant improvements in the bandwidth of a green LED structure [18]. The InGaN/GaN LED of a conventional surface emitting design was grown by metal organic vapour phase epitaxy on a sapphire substrate with a 5 quantum well active region that emits at 510 nm. The total output power from the LED measured in an integrating sphere was 1.2 mW at a drive current of 20 mA. Over a temperature range of -40^{o}C to +70^{o}C the output power from the LED reduces by only -1.14 dB.

The device has been used to transmit data at 200 Mbps over 100 m of low NA SI-POF by driving the device at 50 mA with no additional peaking circuit, the eye diagram for which is shown in Fig.2. As can be seen the eye diagram has a good open eye with a bit rate error estimated to be $1x10^{-9}$. These results indicate that such LEDs are excellent candidates for use in rugged environments where the length of the POF link needs to be maximised such as industrial field buses or where shorter links need to tolerate high bending losses such as car harness.

The AGETHA consortium are also attempting to further improve the performance of green LEDs by developing a green RCLED structure [19]. These devices as indicated in Fig. 3 are grown on insulating sapphire substrates and consist of a 20 pair AlGaN/GaN DBR low reflectivity bottom mirror, a

2λ InGaN/GaN quantum well active region while the top mirror, unlike 650 nm RCLEDs, is formed by a high reflectivity metal mirror, predominently silver. This means that these green RCLEDs are bottom emitting devices and must be flip-chiped prior to die attach.

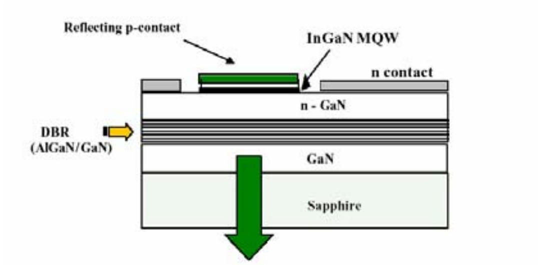

FIG.3 Schematic diagram of a substrate emitting InGaN RCLED.

The technological challenge in developing these green RCLEDs is the growth of high quality AlGaN/GaN DBR mirrors which is frustrated by the large lattice mismatch between GaN and AlN and the low refractive index contrast achieved. As a consequence the green RCLED uses the semiconductor DBR as the low reflectivity extraction mirror and a high reflectivity metal top mirror that also forms the p-type Ohmic contact. Due to the thin n-type GaN layer the series resistance and turn-on voltage tend to be higher than for a surface emitting device. Nevertheless, angle resolved electroluminescence measurements unequivocally demonstrates the presence of a resonant cavity. Such devices have been used to demonstrate data transmission of 250 Mbps.

7. Conclusions

It is clear that the significant effort continues to be expended in the development of advanced sources for PMMA based POF. It is likely however that the various sources under development will be optimized for different applications for example, RCLEDs for IEEE 1394.b and green high-speed LEDs for field buses. In addition to improvements sought in intrinsic emitter performance it should also be stressed that device packaging plays a significant role and it is the combination of device and package that needs to be fully optimised.

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