CWDM based HDMI interconnect incorporating passively aligned POF linked optical subassembly modules

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Abstract: A four-channel transmitter OSA (TOSA) and a receiver optical sub-assembly (ROSA) module were presented. They take advantage of a coarse WDM (CWDM) scheme, employing two types of VCSELs at 780 and 850 nm, where no wavelength filters are involved in the TOSA. The ROSA and TOSA were constructed through a fully passive alignment process using components produced by virtue of a cost effective plastic injection molding technique. In order to build a high quality optical HDMI interconnect, four channel optical links between these modules ware established via two graded-index plastic optical fibers (GI-POFs). The HDMI interconnect was thoroughly evaluated in terms of the alignment tolerance, the light beam propagation, and the data transmission capability. For the ROSA, the measured tolerance, as affected by the photodiode alignment, was ~45 μm and over 200 μm for the transverse and longitudinal directions, respectively. For the TOSA, the tolerance, which is mostly dependent upon the VCSEL alignment, was ~20 μm and more than 200 μm for the transverse and longitudinal directions, respectively. The beam profiles for the TOSA and ROSA were monitored to confirm their feasibility from the optical coupling perspective. A digital signal at 2.5 Gb/s was efficiently transmitted through the HDMI interconnect with a bit error ratio of below 10^{-16}. A 1080p HDMI signal from a Blu-ray player was delivered through the interconnect to an LCD monitor and successfully displayed a high quality video.

OCIS codes: (200.4650) Optical interconnects; (220.1140) Alignment; (080.2205) Injection molding; (140.7260) Vertical cavity surface emitting lasers; (230.0230) Optical device.

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1. Introduction

Recently, cost effective short-distance interconnects have earned a vast amount of attention due to the rapidly rising demand for large capacity transmissions of video/data/audio signals for such consumer electronic gadgets as smart phones, TVs, game consoles, etc. Optical interconnects have started to become a viable alternative to conventional copper based cables, which pose several critical issues in terms of bandwidth, electromagnetic interference, thermal management, and weight [1, 2]. The availability of low-cost optical subassembly modules (OSAs) is essential to accelerating the penetration of optical interconnects into the market [3–6]. Such modules can be achieved by primarily reducing the cost of light sources and connecting fibers, and by facilitating the assembly procedures [7–10]. Toward this end, various types of OSA modules have been reported that use VCSELs in conjunction with plastic optical fibers (POFs) [8, 11–13]. Previous optical high-definition multimedia interface (HDMI) interconnects are mostly composed of OSA modules, which are prepared via an active assembly scheme, based on a WDM scheme resorting to WDM filters [14].

In this paper, both a four-channel coarse WDM (CWDM) based transmitter OSA (TOSA), requiring no expensive wavelength filters, and a similar receiver OSA (ROSA) module were proposed incorporating VCSELs operating at 780 and 850 nm wavelengths. They were constructed by means of a passive alignment scheme; the constituent parts were manufactured through a precision injection molding technique. Ultimately, a high quality optical HDMI interconnect was constructed by integrating the ROSA with the TOSA via a pair of graded-index plastic optical fibers (GI-POFs). Both of the modules were rigorously characterized through the observation of the optical coupling efficiency in regards to the beam propagation and the alignment tolerance. The proposed HDMI interconnect was evaluated in terms of the data transmission at 2.5 Gb/s for the purpose of guaranteeing its applications to 12 bit color depth full HD video signals.

2. Proposed optical HDMI interconnect and its design

Figure 1 illustrates the configuration of the proposed optical HDMI interconnect, which is composed of four channel ROSA and TOSA modules and a pair of GI-POFs. The four channels are composed of an upper pair, Ch1 (λ_1) and Ch2 (λ_2), and a lower pair, Ch3 (λ_2) and Ch4 (λ_1). The ROSA includes collimating lenses, a 780-/850-nm wavelength filter, focusing lenses integrated with a prism, and photodiodes (PDs). The TOSA is made up of two different VCSELs operating at 780 and 850 nm, collimating lenses in conjunction with a prism, and focusing lenses. Considering that both of the upper and lower pairs share the same operation, the operation of the proposed interconnect is elucidated just for the case of the upper pair as follows: For the TOSA, the two beams emerging from the VCSELs responsible for the Ch1 (λ_1 = 850 nm) and Ch2 (λ_2 = 780 nm) signals are almost completely reflected by the prism via the total internal reflection and collimated by the collimating lens. These two collimated beams impinge upon an identical focusing lens at an off-axis so as to be focused and couple to a single POF, thereby eliminating the demands for WDM filters, which are indispensable in the conventional schemes. For the ROSA, the two beams coming out of the POF are collimated and split into different paths by the wavelength filter, and finally focused onto the relevant PDs. The filter plays the role of selectively reflecting and transmitting the beams at λ_1 = 850 nm and λ_2 = 780 nm, respectively.

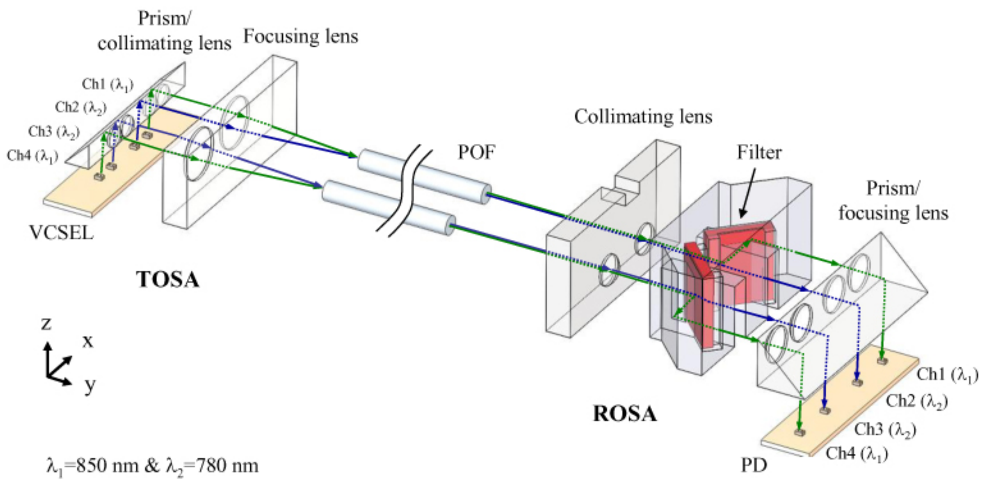


Fig. 1. Proposed optical HDMI interconnect incorporating the CWDM based ROSA/TOSA modules.

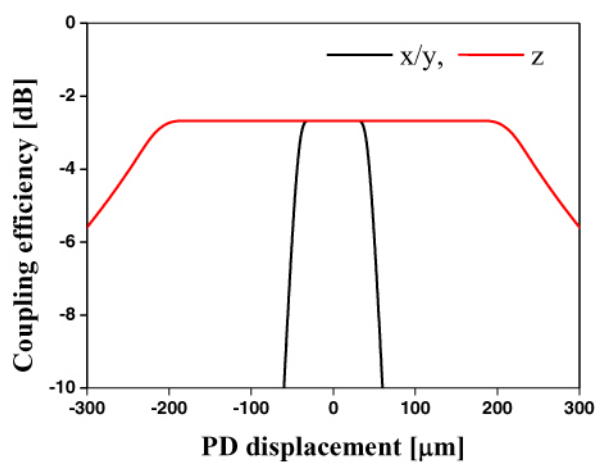
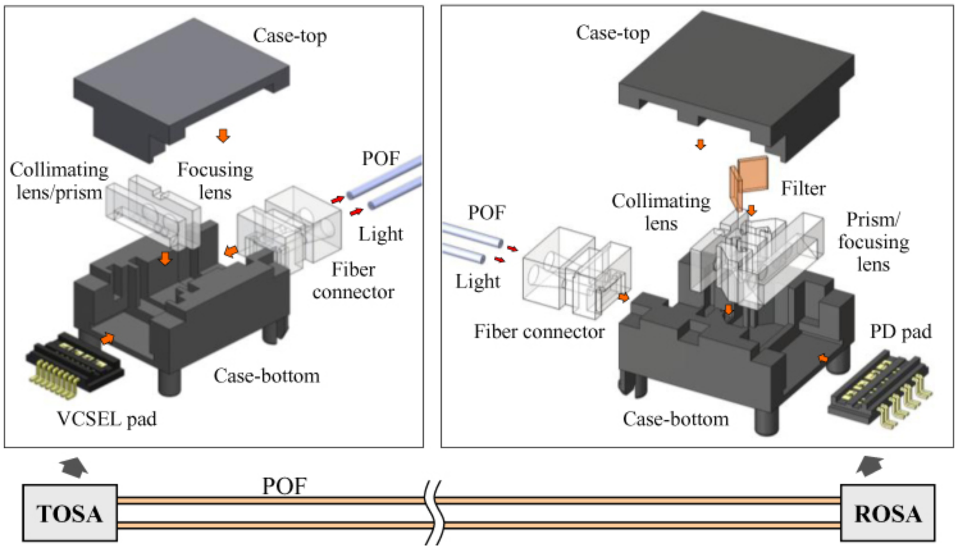


Fig. 2. Calculated POF-to-PD coupling efficiency dependent on the PD displacement.

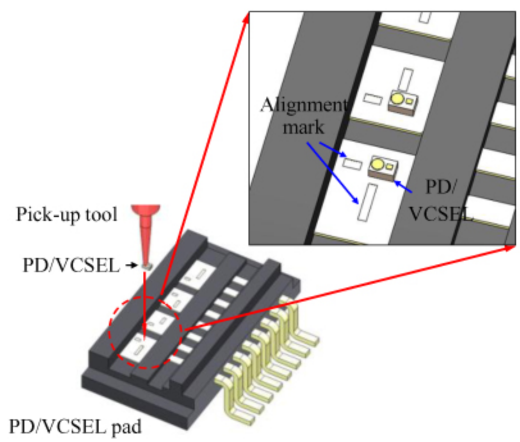
The proposed modules were designed to have a relaxed structural tolerance, allowing for a fully passive alignment process. The design parameters associated with the OSA modules are as follows: The GI-POF has a core of 120 µm in diameter leading to a numerical aperture of ~0.185, whereas the PD has a 100-µm diameter aperture. The lens and prism are both made of polycarbonate with a refractive index n = 1.586. The divergence angle of the VCSEL is ~25°. For the ROSA module, the alignment tolerance of the PD was first numerically inspected with respect to the POF-to-PD coupling efficiency. As shown in Fig. 2, the 3-dB tolerance to the PD alignment was about 40 µm and over 200 µm for the transverse x/y axes and longitudinal z axis, respectively; the best coupling loss was 2.5 dB, which is mostly attributed to the Fresnel loss. For the TOSA, the tolerance to the VCSEL alignment was similarly analyzed to be about 20 µm and over 200 µm for the transverse and longitudinal directions, respectively; the minimum coupling loss was 3.9 dB [7].

3. Construction of the proposed HDMI interconnect and its characterization

The procedure used to implement the optical HDMI interconnect is described in Fig. 3(a), wherein the ROSA module is connected to the TOSA module via a pair of GI-POFs. Both of the OSA modules were built by utilizing the proposed passive alignment scheme, entailing no active monitoring. For the ROSA, the alignment between the POF and PD was fulfilled in such a way that the PD pad, containing the PDs and the pin connect, was inserted into the case-bottom and then secured by the case-top. For the TOSA, the VCSEL was aligned to the POF in a similar manner. As indicated in Fig. 3(b), the VCSELs and PDs were appropriately mounted on the pad with a pick-up tool with the assistance of an alignment mark.



(a)



(b)

Fig. 3. (a) Procedure used to build the ROSA/TOSA (b) Precision aligning of the PDs/VCSELs.

The completed optical HDMI interconnect, where the ROSA is combined with the TOSA through the GI-POF, available from Chromis Fiberoptics, is displayed in Fig. 4(a). The lens, the fiber connector, and the case for the ROSA/TOSA modules were prepared by means of a high precision injection molding technique, enabling volume production. The prism, focusing

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lens, collimating lens, and fiber connector were all made of transparent polycarbonate (PC) with the melting temperature T_m=267°C, whereas the case-top, case-bottom, and pad were made of polyamide with a T_m=260°C. The footprint for the ROSA and TOSA is 15(L)*12(W)*4.5(H) mm^3 and 13.6(L)*12(W)*4.1(H) mm^3, respectively. The PDs and VCSELs mounted on the pad are displayed in Fig. 4(b), wherein a custom made tool was utilized to accurately pick up and place them on the metal pad, coated with a silver epoxy, with the help of an alignment mark. As shown in Fig. 4(c), the POF was firmly secured to the fiber connector with a UV epoxy.

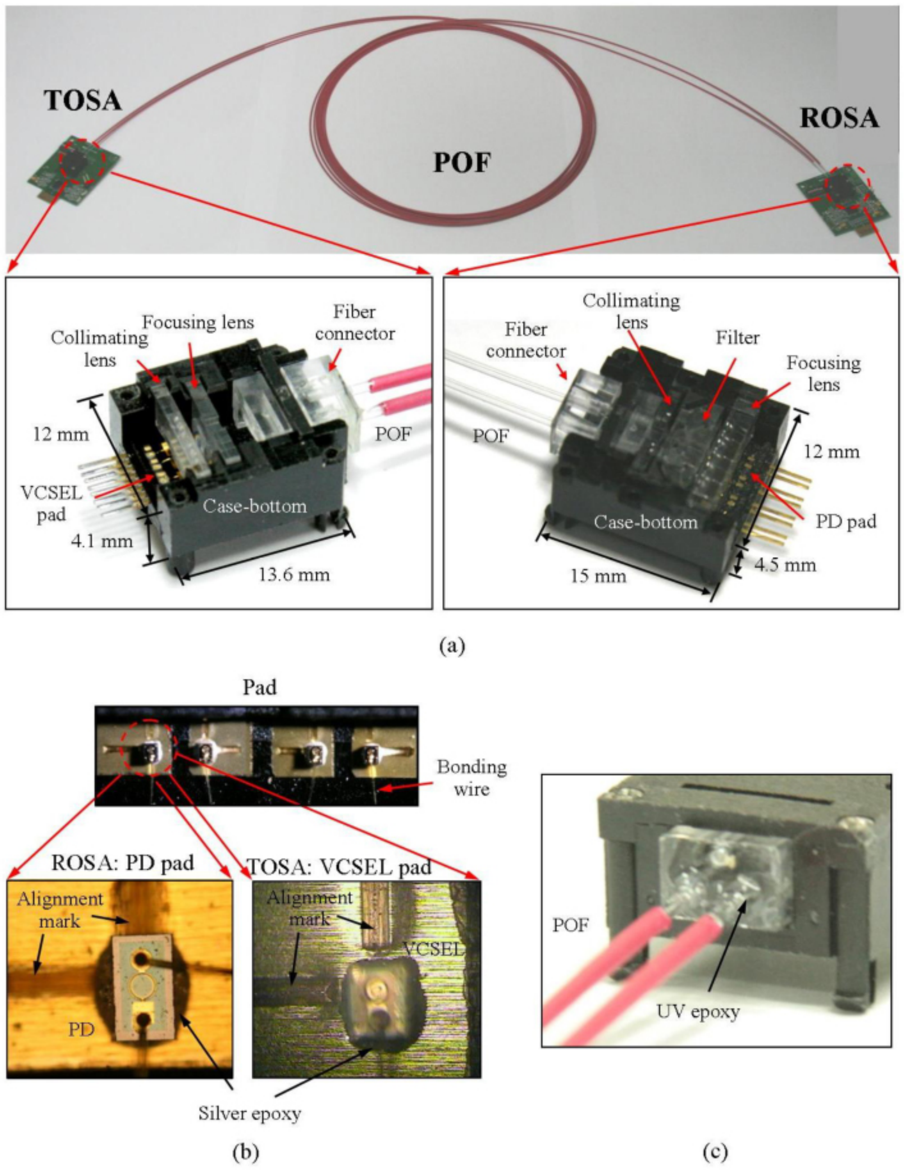

Fig. 4. (a) Completed optical HDMI interconnect (b) Mounting of the PDs/VCSELs (c) POF connection.

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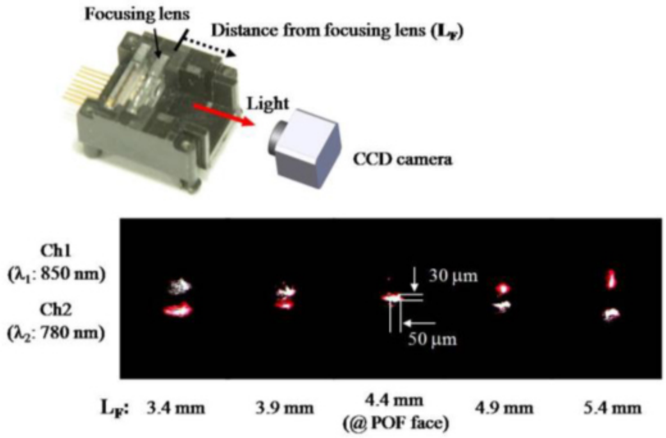
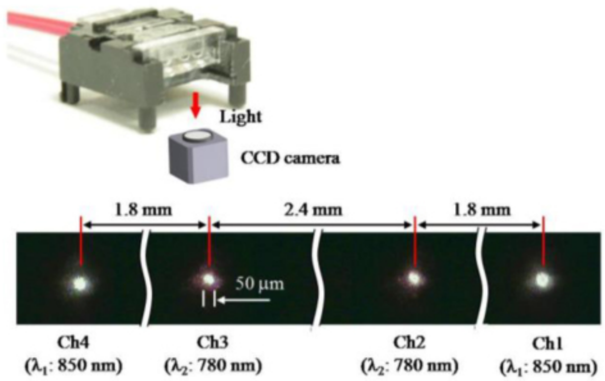


(a)



(b)

Fig. 5. Captured beam profiles for (a) TOSA module (b) ROSA module.

In order to verify the performance of the prepared HDMI interconnect, we investigated the transfer characteristics of the TOSA and ROSA modules, followed by the signal transmission between them via the POF. The OSA modules were primarily assessed in terms of beam propagation as well as alignment tolerance. The observation of the beam propagation in the modules is essential to the estimation of the feasibility of their configuration. Figures 5(a) and (b) reveal the beam profiles, captured by a CCD camera, for the TOSA and ROSA, respectively. For the TOSA, the light beam was specifically imaged in the region around the focal point of the focusing lens. The observation point was equivalent to the distance from the focusing lens L_F, ranging from 3.4 to 5.4 mm. The beams for Ch1 and Ch2 converged to the focal point at L_F = 4.4 mm, where they exactly overlap each other providing a spot size of 50 μm; they diverged again thereafter. Considering the facet of the POF is located right at the position for L_F = 4.4 mm, it is obviously confirmed that the two beams can simultaneously couple to a single POF, as intended. As depicted in Fig. 5(b), the pattern of the light beams exiting the ROSA module was then detected at the focal point of the focusing lens, where the PD is normally located, 300 μm from the prism. For all of the four channels, the resulting beam profiles offered a spot size of about 50 μm. The distance between the beams for Ch1 (Ch3) and Ch2 (Ch4) was observed to be 1.8 mm, and the gap between the beams for Ch2 and Ch3 2.4 mm. Taking into account the fact that the distances among the channels precisely

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match the designed values, we were assured that the incoming beams can be safely received by the PDs, as desired.

Next, we attempted to explore the alignment tolerance for the OSA modules as it pertained to the optical coupling efficiency. For the ROSA the optical coupling with respect to the misalignment incurred during the PD mounting was monitored. As plotted in Fig. 6, the optical coupling from the POF to PD was measured by deliberately displacing the PD with a 10-µm and 20-µm step size in the x/y and z axes, respectively. The 3-dB tolerance for the x, y, and z axis was approximately 53, 49, and >200 µm, respectively; the POF-to-PD coupling loss was 2.9 dB. For the TOSA, the tolerance in relation to the VCSEL mounting was addressed by checking the VCSEL-to-POF coupling efficiency. The 3-dB tolerance for the x, y, and z axis was about 22, 18, and >200 µm, respectively, when the POF-to-PD coupling loss was 3.9 dB. As a result, these experimental results decently agreed with the numerical results. The optical crosstalk between Ch1 and Ch2 was then examined for the ROSA module: The optical output resulting from the PDs for Ch1 and Ch2 was acquired when either VCSEL for Ch1 or Ch2 was turned on. The observed channel crosstalk was well below –23 dB.

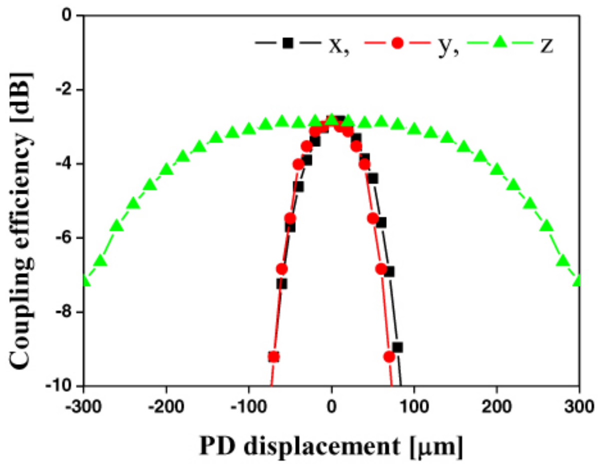

Fig. 6. Measured POF-to-PD coupling efficiency with the PD alignment.

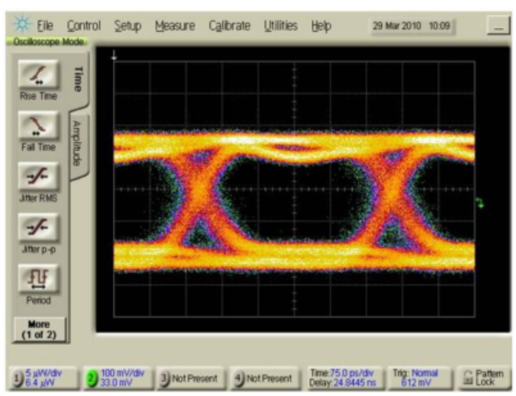

Fig. 7. Observed electrical eye pattern for the data transmission at 2.5 Gb/s.

Finally, the high speed data transmission through our HDMI interconnect, employing a 15-m long POF, was performed through the use of a 2.5 Gb/s 2^{31}-1 pseudorandom. Its components, such as the VCSELs, the PDs and the drive chips, were specifically chosen to work at the equivalent speed in view of its applications to 12-bit color depth full HD video transmissions. The perfluorinated GI-POF is reported to have an optical loss of <60 dB/km at

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850 nm and cause no significant dispersion for a speed of up to 10 Gb/s over a transmission length of 100 m [15]. The electrical eye pattern for the receiver was measured using an Anritsu MU163220C pulse pattern generator (PPG), an evaluation board, and an Agilent 86100C digital communications analyzer. An acceptable electrical eye pattern was attained as shown in Fig. 7; the bit error ratio was found to be below 10^{-16}. Finally, as displayed in Fig. 8, a full-HD 1080p HDMI video clip, taken from a Blu-ray player, was successfully conveyed to an LCD TV using the manufactured interconnect via a couple of 15-m long GI-POFs. The maximum transmission length for the proposed HDMI interconnect is estimated to be ~100 m, taking into account the GI-POF attenuation of <60 dB/km at λ = 850 nm, the VCSEL output power of >0 dBm, the maximum sensitivity of the ROSA drive chip of about −12 dBm, and the loss associated with the TOSA/ROSA of ~5.8 dB. It can be efficiently extended by enhancing the sensitivity of the ROSA drive chip. It is also remarked that the operation speed of our interconnect is currently limited to about 5 Gb/s, which is largely affected by the unwanted noise coupling caused by the parasitic capacitance of the metal pads.

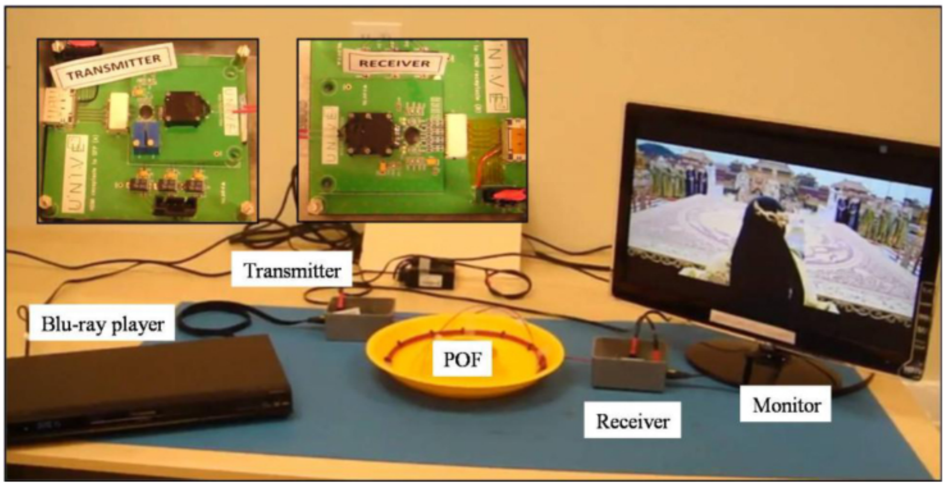

Fig. 8. Demonstration of the Full HD (1080p) video transmission.

4. Conclusion

In summary, a passively assembled CWDM based optical HDMI interconnect was cost effectively manufactured by linking a ROSA module to a filter free TOSA module via a couple of GI-POFs, which were produced by putting together the elements prepared using a precision plastic injection molding. The structural tolerances were sufficient to enable the transmission of high speed signals at 2.5 Gb/s. The HDMI interconnect was then practically applied in order to convey 1080p HDMI video data.

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