Packaging of optoelectronic and RF components with shared elements for dual-mode wireless communications

J. Liao, J. Zeng, S. Deng, V. Joyner, A. Boryssenko, K. Connor and Z. Rena Huang

The development of a new hybrid packaging method is reported, where the front end radio frequency (RF) element, namely a modified quasi-Yagi antenna, is integrated with an optical transmitter and an optical receiver on single PCB for dual-mode, i.e. RF/free space optical communication. The VCSEL and the *pin* diode are placed on the antenna directors to share the common metal pads on the Duroid (RT 6010) board. The modules have demonstrated dual-mode wireless communication capability, i.e. RF and free space optics. Though the RF channel induces noise to the optical transmitter/receiver due to electromagnetic coupling between closely-spaced RF and optical circuits, a data rate of 2.5 Gbit/s is demonstrated for the optical channel.

Introduction: Hybrid communication systems, combining the free space optical (FSO) and radio frequency (RF) transmission, will play a key role in providing future-generation networks with increased data capacity and agility. A wireless network with hybrid FSO/RF communication capability is particularly attractive, because it will permit increased system bandwidth, reduced power consumption, wide coverage range, and network reliability. To accomplish this goal requires the development of novel packaging and integration approaches for optical and RF transceiver components in a single module.

The challenge in integration and packaging of optical components with RF antennas first lies in the large dimension discrepancy between the two types of the devices. In X-band, the antenna resonance dimension is about 1 cm, whereas the die size of optical elements is $\sim$300 μm. Attempts have been made for RF/FSO module integration. One method is to place the optical elements in the RF signal path with a shared lens system [1]. This approach is feasible only for certain types of antennas, and is not suitable for planar microstrip antennas. Another approach is monolithic integration of the antenna on a CMOS or BiCMOS chip [2, 3], which is an attractive solution for simplification in packaging. However, the antenna radiation efficiency is low owing to excitation of substrate modes in the Si substrate. The hybrid packaging, where the antenna is integrated on a low dielectric substrate, and the rest (optical elements and circuits) is fabricated on semiconductor substrates, becomes the most widely used approach in RF/FSO packaging [4].

In this Letter, an alternative hybrid packaging scheme is investigated in order to create an ultra-compact RF/FSO module for combined RF/FSO wireless communication. Taking advantage of the dimension difference between the RF antenna and the optical frond-end elements, we placed the optical elements on the antenna radiation pads to share a common area, leading to a compact RF/FSO module. In this packaging scheme, coupling from the RF radiation to optical transmitters and receivers is a concern. A detailed analysis of coupling from RF channel to FSO channel will be presented in this Letter. We prototyped an RF/FSO module for dual-mode wireless communication. In duplex dual-channel communication configuration, the FSO channel has demonstrated a data rate of 2.5 Gbit/s.

RF/FSO module packaging: The baseline of the RF channel is a modified, split dual-director quasi-Yagi antenna [5, 6] operating at X-band. It is fabricated with a standard 25-mil Duroid substrate (RT 6010), which has the permittivity of $\epsilon_r = 10.2$, and the loss tangent of 0.0023 at 10 GHz. The quasi-Yagi antenna consists of a microstrip transmission line, a balun, a coplanar stripline, a dipole driver, two split directors, and a truncated ground plane on the backside of the substrate. The measured return loss of the fabricated quasi-Yagi antenna is below 10 dB in the frequency range of 8.5–10.5 GHz. Furthermore, the antenna radiation direction is set normal to the system board ground in the process of integration. This matches the pointing RF/FSO directions without degradation of antenna beam shape and return loss in a narrow band around 10 GHz.

In this new packaging design, the dual split directors of the antenna on the Duroid substrate not only guide the electromagnetic wave, but also provide electrical contacts for mounting bare die optoelectronic devices: a vertical cavity surface emitting laser (VCSEL) and a *pin* photodiode (*pin*). The cathode connection of the bare die devices are attached to one of the antenna director pads using conductive epoxy adhesives (SEC 1233); and the anode connection is wire bonded to the remaining antenna director pad. The antenna director pads are electrically connected via tin/lead wires to a multilayer printed circuit board mounted with supporting front-end transimpedance amplifier (optical receiver) and laser driver (optical transmitter) circuits. Fig. 1 shows both RF/FSO modules with a quasi-Yagi antenna packaged with a VCSEL and a *pin*.

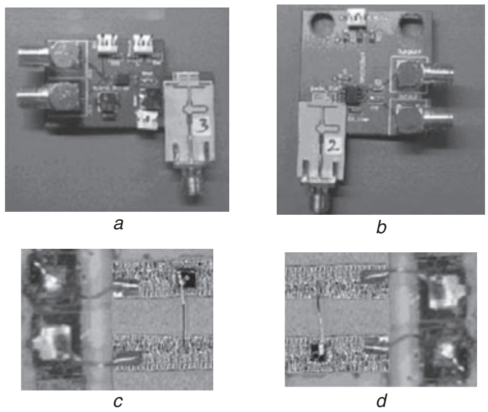

Fig. 1 *Photos of fabricated RF/FSO module*

a RF/FSO transmitter
b RF/FSO receiver
c Packaging of VCSEL to antenna on transmitter PCB
d Packaging of *pin* to antenna on receiver PCB

Measurement results and analysis: The two RF/FSO modules are first tested independently with the RF antenna feed on and off. For the RF/FSO-transmitter module, the laser driver circuit is driven by a differential, PRBS signal at 2.5 Gbit/s. The RF antenna is turned on at a power level of 14 dBm at 10 GHz during the operation of the optical transmitter. Electromagnetic coupling is exhibited because the same structural element is shared by the antenna (director) and optical circuit (pads). Full-wave electromagnetic simulations using either HFSS or CST Microwave Studio® indicates 15–20 dB coupling between the optical and RF ports which is observed around the antenna 10 GHz resonance frequency for the layouts in Fig. 1. This coupling is negligible in the case of the optical transmitter but a notable effect on the optical receiver is exhibited. Simulation results show an induced current magnitude of 2.5 μA at an RF power level of 30 dBm, which is negligible compared to the VCSEL modulation current set to 6 mA. This is confirmed by the measured eye diagram of the optical transmitter using a commercial optical receiver which shows no degradation when the antenna is turned on.

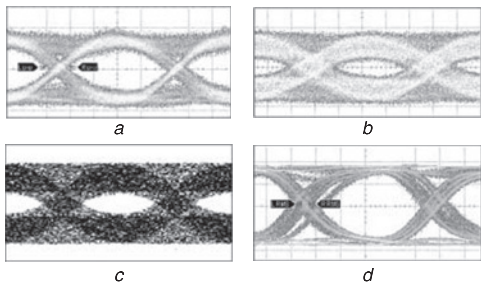

Fig. 2 *Eye diagram at 2.5 Gbit/s ($2^7 - 1$ PRBS) of optical receiver*

a Measured result when antenna turned off
b Measured result when antenna fed by 14 dBm power
c Simulated eye diagram for 15 dB optical-to-RF coupling
d Measured result of FSO link when antenna fed by 14 dBm power

For the RF/FSO-receiver module, the quasi-Yagi antenna is fed with three power levels (0, 7, 14 dBm) CW signal to evaluate the noise current induced at the bonding wire when the antenna is radiating. The RF/FSO receiver has two basic operation modes. For a true duplex operation, the antenna in the optical receiver side may be in the mode of transmitting signals. A Matlab model is used to predict impact of the electromagnetic coupling on reception of the $2^7 - 1$

PRBS optical signal transmitted at 2.5 Gbit/s rate. For this, an RF time harmonic signal is added to the optical channel as a noise component with magnitude corresponding to the computed inter-channel coupling and random phase because the optical and RF signals are phase unlocked. For the same signal and bit rate, the simulated eye diagram (Fig. 2*c*) is a good match to those measured eye diagrams of the RF/FSO receiver shown in Figs. 2*a* and *b*. However, we need to note that the testing condition mentioned above is evaluated for the worst case in terms of coupling from the RF channels to the FSO channels. When the antenna is working in its receiving mode, the EM wave induced noise current to the photoreceiver should be minimal.

The dual-mode wireless communication prototype consisting of a pair of RF/FSO transmitter and receiver modules separated by 0.25 m is tested. Two lenses with 25 mm focal length are used to collimate and focus the laser beam. The antenna in the RF/FSO transmitter is fed with a signal at 14 dbm at 10 GHz. At the receiver, the antenna receiving power is measured by a spectrum analyser (Agilent E4407B). The measured antenna receiving power is −14 dBm. The measured FSO link eye diagram at 2.5 Gbit/s is shown in Fig. 2*d*. The far-field antenna radiation pattern is measured using the NSI near-field scanner (Fig. 3). These patterns suggest no noticeable change compared to the condition when optical elements are turned on/off. The pattern shapes demonstrate some angular variations and ripples caused by the nearby optical circuit components especially in the case of the transmitter board (Fig. 1*a*). These pattern features are not system critical and will be tackled in future studies.

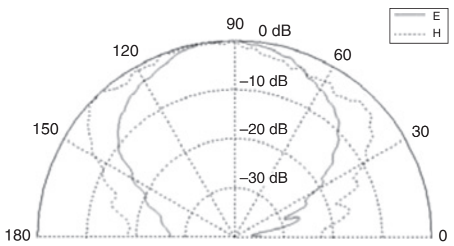

Fig. 3 *Measured radiation pattern of antenna on receiver board at 10 GHz*

Conclusions: A novel hybrid RF/FSO transceiver module is investigated for the first time, and the packaged modules are prototyped for a dual-mode RF/FSO communication system. The new packaging approach reveals that it is possible to use the metal pads of a planar antenna as the mounting pads for optical elements, leading to an ultra-compact hybrid RF/FSO package design through the shared area of the RF and FSO transmitter and receivers. The space sharing between the RF and the optical circuit component leads to their electromagnetic coupling appearing as an additional interference signal. Analysis shows that the RF induced noise is negligible for the transmitter, but degrades the signal integrity of the optical receiver. A dual mode of RF/FSO transmitter and receiver pairs are demonstrated with an optical transmission rate of 2.5 Gbit/s.

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