Optically Powered Low-Energy Demarcation Device for Monitoring FTT*x* Networks

M. Roeger[1], B. Hiba[1], M. Hoh[1], J. Hehmann[2], T. Pfeiffer[2], M. Huebner[3], J. Becker[3], J. Leuthold[1], W. Freude[1]
1: Institute of Photonics and Quantum Electronics, Karlsruhe Institute of Technology, Engesserstr. 5, 76131 Karlsruhe, Germany
Tel.: +49 721 608-2486, Fax: +49 721 608-2786, e-mail: <Moritz.Roeger|Wolfgang.Freude>@kit.edu
2: Alcatel Lucent, Bell Labs Germany, Lorenzstrasse 10, D-70435 Stuttgart
3: Institute of Information Processing Technology, Karlsruhe Institute of Technology, Vincenz-Prießnitz-Str. 1, 76131 Karlsruhe, Germany

Abstract: We demonstrate an energy-autarkic FTT*x* monitor. A special protocol and sophisticated hardware reduce the electrical operating power to 0.7µW, which can be delivered by an optical supply signal of only 5µW/monitor at a separate wavelength.

OCIS codes: (060.0060) Fiber optics and optical communications; (120.0280) Remote sensing and sensors; (060.4250) Networks; (060.4256) Networks, network optimization

1. Introduction

The prevailing access network technology will be based on extended-reach passive optcal networks (PON) combined with wavelength division multiplexing (WDM) techniques. Such networks connect cabinets, buildings or even homes to a central office (CO) and are denoted as fiber-to-the-*x* systems (FTT*x* with *x* = C, B, H for *c*abinet, *b*uilding, *h*ome). They are expected to reduce cost in the optical access range, and to provide significantly increased data rates. For the operators and subscribers, network availability as well as network security will become increasingly important, and operators ask for solutions to monitor and protect their infrastructure on the physical layer [1–4].

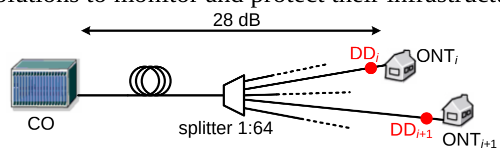

Fig. 1 Optically powered demarcation devices DD*i* (•) in an FTT*x* network for monitoring the operator-subscriber interface to ONT*i*.

At so-called demarcation points different optical network segments have to be separated to define the responsibilities of operator and subscriber. For a PON system operator, there is presently no means available to assure proper performance of a fiber link up to the customer premises unless an active optical network termination (ONT) is attached to the line. Therefore, we propose using a traffic-transparent energy-autarkic demarcation device (DD), which is located at the demarcation point (see Fig. 1) and can be interrogated by the CO [1, 5].

An energy-autarkic DD could draw its energy either from a long-life (20 years) battery, or from optically transmitted energy [6]. Operators express reservations about battery-powered devices, but could be willing to supply optical power via one dedicated wavelength channel to a large number of DD. In both cases the electrical power requirements need be minimum.

Here, we describe a low-energy DD supplied with a 5 µW optical power channel, and an appropriate protocol. The DD is transparent for data traffic, but responds to a low-bitrate control signal which the CO superimposes to the optical data stream.

2. Demarcation device

The demarcation device connects the CO via the operator's network with the subscribers' premises, see Fig. 2. CW light provided by the CO (5 dBm, 3.2 mW) at the power supply wavelength λ_{pow} is dropped by a WDM coupler, fed to the power converter (–23 dBm, 5µW) and converted to electrical energy (–31 dBm, 0.8 µW). The CO sends payload data (3 dBm) to the subscriber (–26 dBm) at a wavelength λ_{data}. In addition, this signal carries a low-bitrate intensity modulation (modulation depth 10 %, ≤ 1 Mbit/s, UART protocol), by which the CO transmits control data to the DD. The perturbation caused by the control data is small enough to avoid frame loss at the ONT as was confirmed by true-traffic measurements. A 5 %-tap connects the data stream to a low-noise receiver (Rx, –37 dBm), which decodes the control data. A directly modulated laser transmitter (Tx, –3 dBm, λ_{DD}) sends information back to the CO via another 5 %-tap. All units are operated by a low-power microcontroller (µC).

In Fig. 3 the components of a DD are shown in detail. The power converter is realized by an array of photodiodes (PD) connected electrically in series, but optically in parallel. Six PD provide the output voltage (1.7 V) needed to run the microcontroller (µC). A capacitor serves as an energy storage. A voltage booster (DC/DC boost) supplies the receiver circuitry (Rx) with larger and stabilized voltage (3.3 V) when required. It is only activated if control

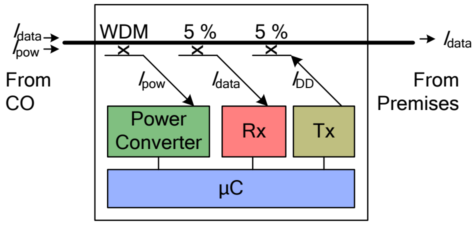

Fig. 2 Block diagram of the DD. The DD is placed before the customer's premises and couples out its supply wavelength channel (Power Converter), taps out 5 % of the data signal to receive (Rx) control signals from the CO and send (Tx) status information back. A microcontroller (µC) is responsible for power management and data communication.

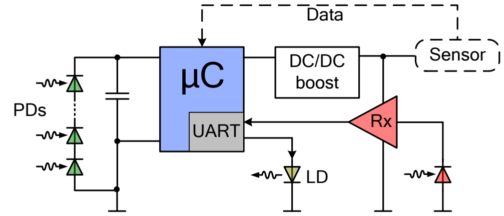

Fig. 3 Detailed schematic of a DD. A multitude of photodiodes (PDs) act as power converter to supply power to the DD. A microcontroller (µC) controls the DD and uses its UART interface for communication. The incoming signals need to be amplified by a receiver amplifier (Rx) requiring a higher drive voltage. This voltage is generated by a DC/DC boost converter. Additionally, different sensors might be added to expand the functionality.

signals are to be detected. For the transmitter a directly modulated VCSEL (LD) is used. Receiver and transmitter are operated using the UART protocol interface of the µC. Additionally, one or a multitude of sensors might be connected to expand the functionality of the DD. The µC has a *sleep mode* where it maintains but an inaccurate clock, and a *snooze mode* during which an accurate quartz clock does the time keeping.

3. Low-energy medium-access control (LE-MAC) protocol

When the DD is fully active, Rx, Tx and µC require a total of about 40 mW (+ 16 dBm) electrical power, which seems to exclude an energy-autarkic operation of the DD with an optically supplied power of 5 µW (–23 dBm). To meet the low power demands an ultra-low duty cycle for the DD is used, Fig. 4: For long time periods (T_{Sleep}, T_{Snooze}) all DD stay in an energy saving *sleep mode* or *snooze mode* where Rx and Tx are switched off. Only during very short time intervals (T_{Wkup} or T_{RxTx}) the devices awake to *active mode* and listen to the CO or communicate with the CO, respectively. The difficulty with the sleep mode, though, is that synchronism with the CO is lost, so that all DD try communicating with the CO at random times. Our *l*ow-*e*nergy *m*edium-*a*ccess *c*ontrol (LE-MAC) protocol exploits the sleep mode while guaranteeing a fixed "rendezvous" time where all DD can individually respond to the CO.

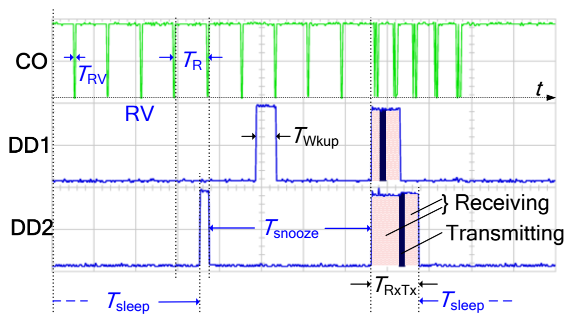

Fig. 4 Operation of two subscribers (DD1, DD2) and a CO running the LE-MAC protocol. Measured signals of CO, DD1 and DD2 are depicted versus time. RV marks a rendezvous signal with time stamp information T_{Snooze}. Details are described in the text.

Fig. 4 shows the measured timing signals of two connected DD. Inside a period larger than T_{Sleep}, the CO broadcasts to the DD a number of R rendezvous signals RV, repeated at intervals $T_R = T_{\text{Sleep}} / R$. The signals RV inform the DD which happen to be presently awake if and when a communication "rendezvous" will be arranged. If no RV signal is received, the DD goes back sleeping after the wakeup time. However, if RV was received (DD1,2), the DD extracts the time stamp for the next rendezvous with the CO, sets a high precision clock, and then goes snoozing for the waiting time T_{Snooze}. Snoozing DD awake exactly at rendezvous time and wait for being addressed by the CO. On reception of its individual address each DD communicates with CO and goes sleeping as soon as the next DD is addressed or after an internal time-out. The LE-MAC protocol offers different timing constants to optimize the mean power consumption [5]. With an ultra-low duty cycle of 10^{-5} for the DD, the mean current and voltage requirements can be tuned to 0.4 µA at 1.7 V.

4. Optical power supply

A single photodiode (PD) illuminated with a power of $P_{\text{opt}} = 5$ µW at a wavelength of $\lambda_{\text{pow}} = 1550$ nm (frequency f_{pow}) delivers an open-circuit voltage $U_{oc,1}$ of about 400 mV. To increase this voltage we use N nominally identical PD connected in series. The incoming light illuminates all PD with equal powers P_{opt} / N. The single-PD open-

NWC4.pdf

circuit voltages $U_{oc,1}$ add up to the N-PD open-circuit voltage $U_{oc,N}$. With ideality factor m, thermal voltage $U_T = kT/e$ (Boltzmann constant k, temperature T, elementary charge e), PD sensitivity $S = \eta e/(h f_{pow})$ (quantum efficiency η, Planck's constant h) and saturation current I_s we find the open-circuit voltages

$$U_{oc,1}\left(P_{opt}\right) = mU_T \ln\left(\frac{S \cdot P_{opt}}{I_s}+1\right), \qquad U_{oc,N} = N \cdot U_{oc}\left(\frac{P_{opt}}{N}\right) \approx N \cdot U_{oc,1} - mU_T \cdot N \ln N \quad \text{for} \quad \frac{S \cdot P_{opt}}{I_s} \gg 1. \tag{1}$$

The short-circuit photocurrent of each PD is $I_{sc,N} = S\,P_{opt} / N$. The measured current-voltage characteristics of a series connection of 4 to 8 photodiodes is shown in Fig. 5 for a total illumination power of P_{opt} = 5 µW (–23 dBm). We used PD with a very low saturation current I_s = 0.3 nA and a high sensitivity S > 0.9 A/W at λ = 1550 nm.

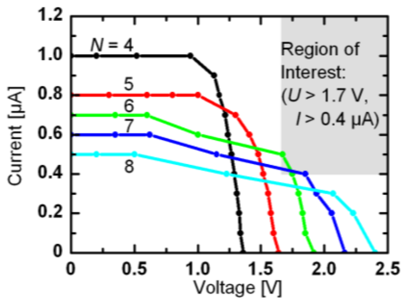

Fig. 5 Current-voltage characteristics of 4 to 8 PD with saturation current I_s = 0.3 nA in an optically parallel and electrically serial connection. Total illumination power was P_{opt} = 5 µW. The grey-shaded rectangle marks the supply power region for the DD.

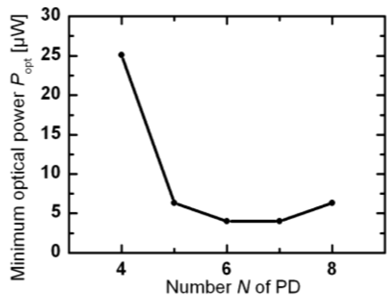

Fig. 6 Minimum optical supply power needed for operating the DD as a function of number N of PD. The minimum supply power for 6 and 7 PD corresponds to an operating point inside the grey-shaded region of Fig. 5.

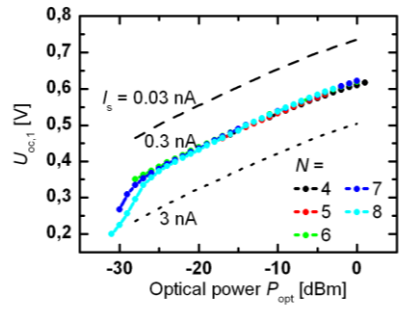

Fig. 7 Single photodiode open circuit voltage $U_{oc,1}$ in dependence of optical power. $U_{oc,1}$ is calculated from measured $U_{oc,N}$ assuming mU_T = 50 mV. For comparison, $U_{oc,1}$ is calculated for I_s = 0.03 nA (dashed line) and I_s = 3 nA (dotted line).

With increasing N the output voltage increases and the output current decreases. For operating the DD a current > 0.4 µA and a voltage > 1.7 V are required, grey-shaded rectangle. A number of N = 6 PD matches the DD requirements "P_{opt} = 5 µW" optimally, Fig. 6. Fig. 7 shows the single-photodiode open-circuit voltage $U_{oc,1}$ calculated from measured open-circuit voltages of a series connections of 4 to 8 photodiodes as a function of the total optical power P_{opt}. The curves virtually coincide, thereby proving Eq. (1) correct. The importance in choosing PD with low I_s is demonstrated with two additional curves in Fig. 7 for I_s = 0.03 nA, 3 nA. The smaller I_s, the larger $U_{oc,N}$ becomes (dashed curve), and thus the available electrical power increases.

Distributing the optical power on an even number of photodiodes can be done by discrete coupler-PD combinations. More advantageous, and required for an odd number, the discrete PD are replaced by sectorized integrated PD. Very good results in saturation current and output voltage have been reported [7].

5. Summary

We demonstrated an optically powered demarcation device for monitoring optical FTT*x* networks up to the subscribers' premises. A sophisticated choice of hardware components in combination with the very energy-efficient LE-MAC communication protocol allows to supply the demarcation device optically with a power of only 5 µW.

This amount of power cannot be extracted from the data signal itself, but operators of a FTT*x* could be willing to provide an extra wavelength channel in an access PON to supply many DD simultaneously. In a PON with an optical distribution network attenuation of 28 dB, one laser located in the OLT delivering a CW power of +5 dBm could supply 64 DD. In the future, specially designed photodiodes optimized for power conversion efficiency in combination with a further decrease in electronic power consumption could enable to operate demarcation devices from a fraction of the data signal power itself.

Acknowledgement We acknowledge support from the BMBF joint project COMAN, funded by the German Ministry of Education and Research under grant 01BP0706.

6. References

[1] Th. Pfeiffer et al., Monitoring and protecting the optical layer in FTTH networks. FTTH Conf., Las Vegas (NV), Oct. 3–6 (2005)
[2] M. Freiberger and S. Huq, "Network element security in optical communications," Proc. OFC 2008, paper NWA1 (2008).
[3] C. C. K. Chan et al., "Novel network architectures for survivable WDM passive optical," Proc. ECOC 2008, paper Th.1.F.6 (2008).
[4] Th. Pfeiffer et al., "Cost efficient non-service interrupting monitoring of optical fiber links in FTTH / FTTB networks," Proc. ECOC 2008, paper Tu.1.F.2 (2008).
[5] M. Roeger et al., "Low-energy demarcation device for monitoring FTTx networks," 10. ITG-Fachtagung Photonische Netze, Leipzig (2009)
[6] M. Roeger et al., "Optically powered fiber networks," Opt. Express **16**, pp. 21821-21834 (2008).
[7] A. G. Dentai et al., "A long-wavelength 10-V optical-to-electrical InGaAs photogenerator," Photon. Technol. Lett. **11**, pp. 114-116 (1999)