Testbed for 100 Gb/s Ethernet

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Abstract— **A testbed implementation for 100 Gb/s Ethernet Optical Time Division Multiplexing experiments is described along with optical subsystems used in its implementation. Testbed potentialities relating to Wavelength Division Multiplexing and hybrid Wavelength/Polarization Division Multiplexing implementations are also described. First experimental results at 20 Gb/s are carried out demonstrating a power penalty lower than 1 dB.**

Keywords-component: Optical networks, 100Gb/s Ethernet, All-optical processing, Optical Time Division Multiplexing (OTDM).

I. INTRODUCTION

Ethernet IEEE 802.3 [1] is the most successful Local Area Networking (LAN) technology. It was developed in the mid-1970's to run over a shared coaxial cable at a maximum speed of 10 Mb/s. In Ethernet, physical medium sharing is guaranteed by the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol. Ethernet physical limitations consist of 2.5 km maximum permitted distance obtainable with a maximum of five 500 m spans separated by repeaters. Ethernet evolved to Fast Ethernet (FE, [2]) running at 100 Mb/s mainly over Unshielded Twisted Pair (UTP) cable. The maximum reachable length in this case is 100 meters with the same Ethernet minimum slot time and 64 byte frame size. It is designed to be essentially used in a full-duplex, point-to-point configuration with a star switched network topology. In 1998 Ethernet evolved to 1 Gb/s ([3]) over fiber while maintaining the simplicity and the frame structure of previous lower speed IEEE 802.3 standards. Gb/s Ethernet adopted a full duplex point-to-point configuration without the CSMA/CD protocol. The 1Gb/s Ethernet spans can reach maximum distances more than 100km with 1000baseZX implementations over single mode Dispersion Shifted (DS) fiber. In June 2002 the optical Ethernet family was extended to 10Gb/s Ethernet through the approval of 802.3ae standard ([4]). The 10 Gb/s Ethernet over fiber operates in full-duplex mode and maintains the same frame format and size of IEEE 802.3. The standard defines two families of physical layer (PHY): LAN PHY operating at a data rate of 10.3 Gb/s and a 64B/66B encoding and WAN PHY running at a data rate compatible with SONET OC-192c (9.953 Gb/s). First 10 Gb/s Ethernet implementations were developed using existing SONET/SDH infrastructures for the transport of Ethernet frames (WAN PHY), thus extending the span of an Ethernet network across different countries. Currently, the most common 10 Gb/s Ethernet optical implementation is referred to as LAN PHY, used for connecting directly to routers and switches. In November 2006 an IEEE study group agreed to target 100 Gb/s Ethernet (100 GbE) as the next version of the technology. The IEEE 802.3 Higher Speed Study Group (HSSG, [5]) has adopted several objectives which direct their current work. These include a maximum reachable length of at least 10 kilometers on Single Mode Fiber (SMF), full-duplex operation, and the utilization of current frame format and size.

According to these objectives, several research activities are focusing on the implementation of a 100 Gb/s Ethernet testbed. In literature two different approaches to generate 100 Gb/s Ethernet signals have been presented. They are based on two different multiplexing techniques: Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM). Dense-WDM (DWDM) is now commonly for long-haul optical transmission system deployments [6]. Nonetheless, TDM is also attractive as it allows more efficient bandwidth utilization and lower power consumption. In particular, for short-haul applications where transmission impairments due to the signal propagation are not significant, it enables use of fewer optical components such as, lasers and filters, thereby potentially offering a more economical solution.

The Time Division Multiplexing can be realized in both the Electrical (ETDM) or Optical (OTDM) domains. To reduce the channel bit rate, sometimes both the techniques are combined through WDM.

The ETDM-based approaches [7-9], exploiting the recent advances in high speed electronics, opto-electronics, and Integrated Circuits (ICs), have shown to be enable selected functionalities operation up to 100 Gb/s. However, at present time further technological advances are required to address issues such as electronic amplification and modulation.

Preliminary OTDM-based 100 Gb/s Ethernet implementations are proposed in [10, 11]. In [11], an implementation based on the serial cascade of two 50 Gb/s Inverse Return to Zero (dark soliton) transmitters using Mach Zender (MZ) modulators is described. The implementation is based on commercially available components optimized for 40 Gb/s applications. However, the stringent pulse source requirements and high

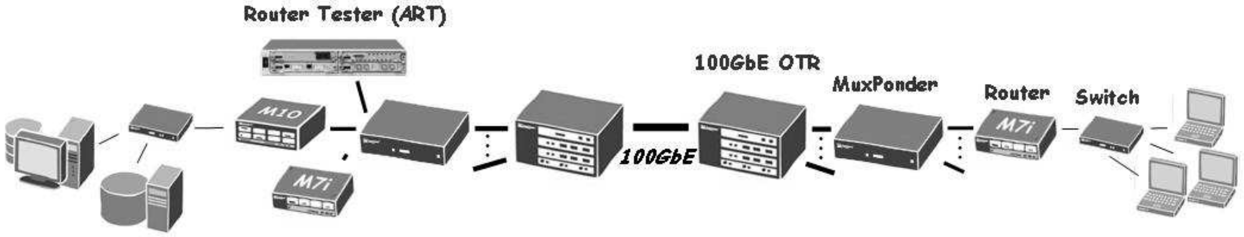


Fig. 1 100 Gb/s Ethernet end-to-end system.

losses arising from parallel modulator arrays present technical challenges and increase the overall cost.

In this paper we describe the implementation of a 100 Gb/s Ethernet testbed (Fig. 1) based on different OTDM solutions. First we introduce all high performance devices and equipment used in the testbed. Then we detail the experimental setup of the 100 Gb/s Ethernet testbed whose main elements are: the sources of native FE traffic (e.g., multimedia workstations), the commercial IP/MPLS Routers that aggregate FE traffic to generate 1 Gb/s Ethernet flows, and the MUX-Ponder that collects eight different 1.25 Gb/s Ethernet flows to generate a single 10 Gb/s Ethernet traffic flow. In the end we focus on the 100 Gb/s Ethernet Optical TransReceiver (OTR) that allows the optical time division multiplexing of up to ten flows at 10 Gb/s Ethernet to generate the required 100 Gb/s Ethernet traffic.

The testbed aim is to investigate the behavior of a complete Ethernet-based network operating up to 100 Gb/s. In particular the objective is to study the requirements and the technical challenges that have to be considered to meet the specifications identified by the IEEE 802.3 HSSG and thus provide the adequate performance level to different critical network applications, such as multimedia services, Grid Computing etc. at very high data rates.

The paper is organized as follows: in section II the testbed scheme is presented and the main equipments that constitute the testbed are described. In section III a 100 Gb/s Ethernet testbed implementation using an OTDM-based solution is proposed and basic system blocks are detailed. In section IV testbed potentialities and further implementations are discussed. Finally, in section V preliminary results are reported.

II. TESTBED DESCRIPTION

In this section we discuss the test bed scheme and introduce high performance devices and equipment that constitutes the testbed (Fig. 2).

A. IP/MPLS Routers

Four IP/MPLS Juniper routers (M7i/M10, [12]) are used in the testbed to collect real data traffic coming from multimedia workstations and LAN PCs as native Ethernet traffic. Each router is currently equipped with at least 4 Fast Ethernet (FE) 100BaseTX interfaces, and at least two Gb/s Ethernet 1000BaseLX optical interfaces. Gb/s Ethernet interfaces operate at 1310 nm for a maximum distance of 10 km. JunOS 7.5 runs on M7i/M10 Juniper routers.

B. Traffic Analyzer and Generators

A traffic analyzer/generator Agilent Router Tester N2X (ART, [13]) is utilized in the testbed to provide realistic Ethernet traffic. The ART is equipped with 20 Fast Ethernet (100BaseTX) interfaces and 8 Gb/s Ethernet (1000BaseLX) optical interfaces. Every ART interface can generate and analyze packets and flows at up to the wire speed. ART also includes software tools which emulate the most widely used network protocols, such as MPLS, RSVP, OSPF, ISIS, BGP and PIM. Several features of GMPLS protocols and extensions are also available. The support of the aforementioned protocols allows the implementation of complex and realistic network clouds around the system under test.

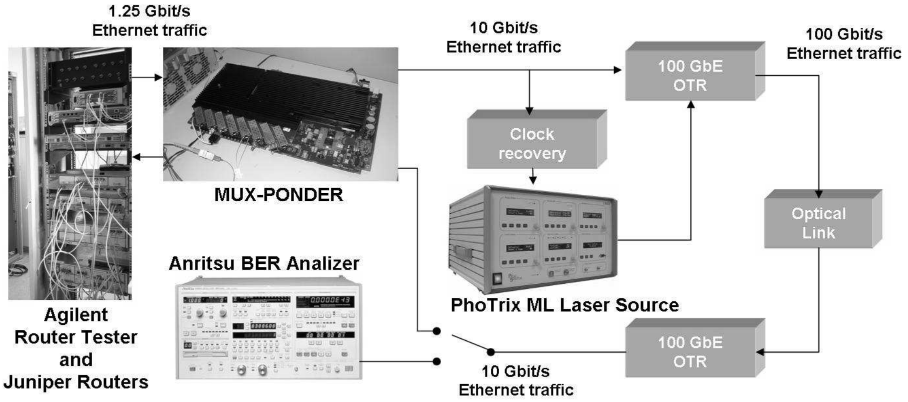


Fig. 2 Block diagram of the implemented testbed.

C. MUX-Ponder

The MUX-Ponder [14] used is a commercial DWDM system card that accepts eight different 1.25 Gb/s Ethernet input flows and generates a single 10 Gb/s Ethernet traffic flow. The MUX-Ponder can perform Bit Error Rate (BER) measurements and Forward Error Correction (FEC) operations.

D. PhoTrix PicoSource

PhoTrix PicoSource [15] (i.e., the Mode-Locked – ML- Laser Source in Fig. 2) is a pulsed laser source generating high-power picosecond pulses at 10 GHz and is based on the harmonic active mode locking technique in a fiber ring laser. The polarization maintaining implementation and the temperature stabilization allow an excellent temporal stability of the signal output. The PicoSource can work at a reference frequency, using the external reference clock input.

The main features of the PicoSource are:

- High quality pulses
- Transform-limited output pulses
- Excellent long term stability
- Wide tunability
- High output power
- Regenerative or external RF controlled
- Available outputs:
    - 2 optical outputs
    - 2 RF clock outputs
    - 1 RF signal monitor

E. Anritsu MP1764C Error Detector

The MP1764C (i.e., the BER analyzer in Fig. 2) is an Error Detector that operates over the 50 MHz to 12.5 GHz frequency range, and is generally used in combination with an MP1763B/C Pulse Pattern Generator to test high-speed digital communication system and high-speed semiconductors. The measurements sequences are pseudorandom (PRBS) pattern, programmable (PRGM) pattern, alternate pattern and zero substitution pattern. The MP1764C has three error detection modes: total error, insertion error, and omission error. The measurements it can provide are error ratio, error count, error intervals (EI), error free intervals (EFI), and clock frequency.

III. CORE TESTBED IMPLEMENTATION

The core part of the testbed refers to the 100 Gb/s Ethernet traffic generation and transmission, mainly focusing on the OTDM solution. The main targets are the study of the 100 Gb/s transceiver and the experimental investigation of the 100 Gb/s Ethernet transmission issues.

The core testbed (Fig. 3) has as input traffic the 10 Gb/s Ethernet optical signal provided by the MUX-Ponder obtained by aggregating the 1 Gb/s traffic flows generated by ART-N2X and Routers. These signals are used to obtain the 100 Gb/s traffic by means of all-optical processing. The testbed includes the presence of a 100 Gb/s Ethernet optical transceiver implementation.

In order to obtain 100 Gb/s OTDM frame, aggregating ten streams at 10 Gb/s, a preliminary NRZ-to-RZ conversion is needed. An Optical Multiplexer permits generation of the 100 Gb/s Ethernet frame before the transmission on the optical link. The 10 Gb/s Ethernet traffic can be added or extracted after the link by means of a ADD/DROP block.

Finally, an Optical DEMUX permits extraction of the 10 Gb/s sequence at the receiver side. The extracted channel is then converted from RZ to NRZ by using a narrow bandwidth filter, and received by the MUX-Ponder or, alternatively, by an error detector device (e.g., MP1764C Error Detector) in order to evaluate the received signal performance in term of bit error rate.

In the following sections the main blocks used for the optical transceiver implementation are described.

A.. NRZ-TO-RZ CONVERTER BLOCK

The NRZ-RZ converter block can be realized by exploiting nonlinear interaction in an optical fiber or a semiconductor device (Fig.4), between the 10 Gb/s NRZ Ethernet signal and a RZ periodic clock with a pulsewidth of <10 ps (which is the 100 Gb/s bit time).

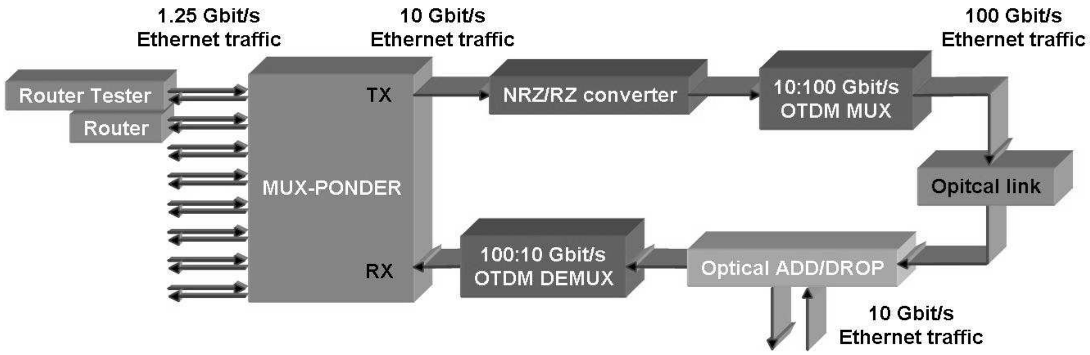


Fig. 3 OTDM-based solution for the testbed implementation.

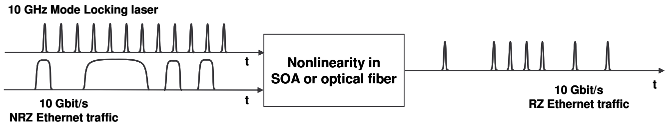


Fig. 4 NRZ-to-RZ conversion block.

For RZ clock generation, it is possible to extract a sinusoidal signal synchronous with the 10 Gb/s NRZ Ethernet flow, directly from the frame by means of an Agilent Clock Recovery module. Driving an Electro Absorption Modulator (EAM), used as pulse generator, with a sinusoidal signal, a Continuous Wave is modulated to obtain a pulse train. In this way 23 ps-long pulses at 10 GHz (see Fig. 5) are obtained. Then an optical compressor, based on soliton propagation in 20 km-long DS (Dispersion Shifted) fiber span, reduces the pulsewidth down to 4 ps. It has been observed that the low quality of the clock causes a high pulse train timing jitter during the propagation in the DS fiber whose chromatic dispersion value is about 1-2 ps/nm km in the C-band, reducing the clock quality and so degrading the conversion block performances.

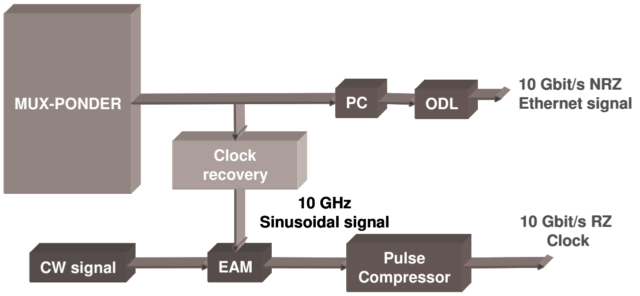


Fig. 5 RZ clock generation using an EAM and a Pulse Compressor.

An alternative solution is shown in Fig. 6. This can be implemented by exploiting a Mode Locked laser source, used as Optical Voltage Control Oscillator (OVCO) in order to directly generate an ultra-short pulse train, without the need of any optical compression stage. The synchronized clock, in this case, can be provided by a mode locked laser realized in an optical fiber-based cavity. It can operate as an optical VCO, inserting into the cavity a variable optical piezo-delay line, driven by a voltage control, that allows modulation of the cavity length and consequently the source repetition rate. Such feature for the RZ clock source can be used to synchronize the Ethernet signal thereby exploiting PLL (Phase Locked Loop) scheme.

Nevertheless, this kind of optical VCO requires a stable clock, extracted from the NRZ signal. Unfortunately, the clock generated by the MUX-Ponder is still not sufficiently stable. This is because the MUX-Ponder card used for the 10 Gb/s frames aggregation has not been designed for a 100 Gb/s Ethernet implementation applications where considerably tighter timing tolerances are required.

One solution could be to provide the MUX-Ponder with a more stable and precise clock. The studies are currently underway to quantify the clock stability required for the synchronization.

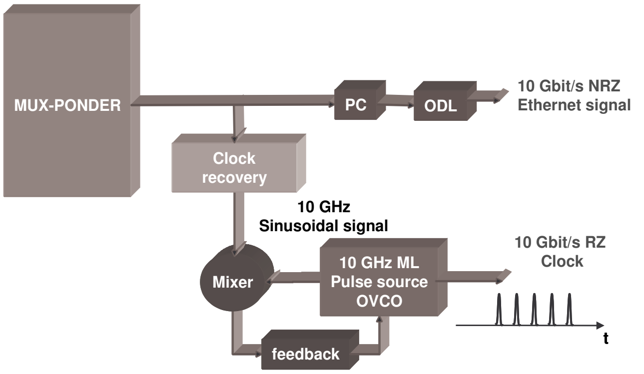


Fig. 6 RZ clock generation using Mode Locked laser source as OVCO solution.

A first experiment employing an EAM as pulsed clock generator, as described in Fig. 5, and 250 m-long High Non Linear Fiber (HNLF) span for the pulsewidth compression has been carried out. By this way 8 ps-long pulses can be obtained. The NRZ-to-RZ conversion block is realized by exploiting Cross Gain Modulation (XGM) nonlinear effect directly in a Semiconductor Optical Amplified (SOA), as reported in Fig.7. In this way it is possible to transfer the data to the pulse train or to a replica of the pulse train at a different wavelength. At the SOA input a Polarization Controller (PC) and an Optical Delay Line (ODL) are used in order to maximize the nonlinear interaction between these signals. By this way the data and the pulse train are time-aligned and the signals have the appropriate polarization required to produce the nonlinear effect. At the output of the SOA an Optical Band Pass Filter extracts the RZ 10 Gb/s Ethernet stream.

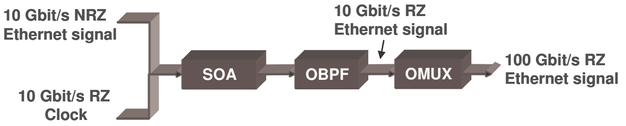


Fig. 7 NRZ-to-RZ conversion block using an SOA-based solution.

B. OPTICAL MULTIPLEXER

An Optical Time Division Multiplexer (OTDM MUX) is needed in order to generate the 100 Gb/s stream (see Fig. 8).

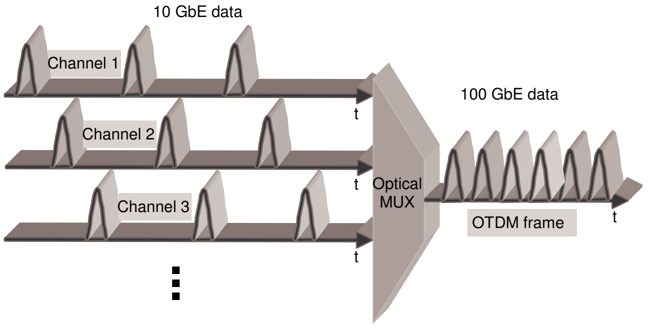


Fig. 8 OTDM Multiplexer.

It aggregates ten tributary optical channels at 10 Gb/s by using optical delay lines with appropriate delay setting on each of the input tributaries, and a multi-input coupler .

C. ADD/DROP MULTIPLEXER

The ADD/DROP Multiplexer can be implemented by exploiting several techniques using nonlinear effects in semiconductor devices or optical fiber (see Fig. 9).

In particular implementations based on semiconductor devices are quite common due to their compactness, integrability, wide optical bandwidth, and high nonlinear efficiency [16, 17]. An alternative approach is to use a highly nonlinear fiber as this can offer effective and very fast optical signal processing in a few meters of fiber [18]. The use of short fiber spans can improve the performance of fiber-based schemes in terms of stability, input requirements and compactness.

A possible solution to implement an optical ADD/DROP multiplexer for time-interleaved optical signals can be achieved by exploiting Cross Phase Modulation (XPM) induced polarization rotation [19] in 1-meter-long bismuth oxide-based fiber.

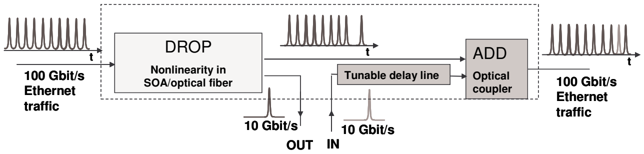


Fig. 9 ADD/DROP multiplexer block diagram.

Using pump pulses at the tributary bit rate and time-coincident with the channel to be dropped it is possible to extract the portion of the signal that has undergone the polarization rotation or, alternately, the part that has not, obtaining the dropped channel and the surviving channels respectively.

By time delaying the pump with respect to the signal, the channel to be extracted can be selected. Successively the use of an optical coupler allows the insertion of a new channel in the same time position of the dropped one.

D. OPTICAL DEMULTIPLEXER

Demultiplexing operation is obtained exploiting ultra-fast nonlinear effects in optical fiber or semiconductor device (see Fig. 10).

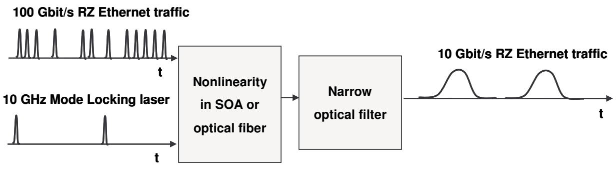


Fig. 10 Demultiplexer and NRZ-to-RZ convetion block operation principle.

SOA-based schemes are generally preferred because of their low cost and simplicity.

In particular a XGM nonlinear effect-based solution is realized in the testbed (see Fig. 11). Coupling a pulse train, synchronized and time-coincident with the frame to be demultiplexed, it is possible to extract the 10 Gb/s tributary Ethernet desired channel at the receiver side. A Polarization Controller (PC) and an Optical Delay Line (ODL) are used at the SOA input in order to maximize the nonlinear effect between the 100 Gb/s Ethernet signal and the 10 Gb/s RZ clock. By this way the data and the pulse train are time-aligned and the signals have the appropriate polarization required to generate the nonlinear effect.

At the SOA output an Optical Band Pass Filter (OBF) extracts the 10 Gb/s RZ Ethernet stream.

In this case the optical clock has been split from the pulse train used in the NRZ/RZ converter block.

After the OPF a narrow-bandwidth filter is needed to the NRZ-to-RZ signal conversion. In fact, a time-widening of the signal improves electronic band-limited receiver performance.

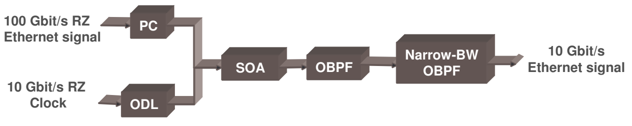


Fig. 11 SOA-based OTDM Demultiplexer.

IV. ALTERNATIVE SOLUTIONS

In order to explain the testbed potentialities, some of the alternative solutions are also summarized. A first competitor to the 100 Gb/s OTDM-based scheme on a single channel, is represented by a WDM-based system solution, using the scheme shown in Fig. 12. In this case ten tributary channels at the repetition rate of 10 Gb/s are multiplied to produce 100 Gb/s Ethernet frame with 10 different wavelengths. The WDM multiplexer and demultiplexer and the ADD/DROP block function can then be implemented for example using commercial devices based on thin film optical filters.

This solution can also be implemented by multiplying four channels at 25 Gb/s or two channel at 50 Gb/s.

Another solution (Fig. 13) that can be adopted to obtain a 100 Gb/s data stream is by using a combination of two orthogonally polarized 50 Gb/s WDM data streams. Also, using a different MUX-Ponder, a 4x25 Gb/s WDM and 4x25 Gb/s WDM/Polarization solutions could be implemented.

Transmission tests can be done using different types and lengths of optical fiber spans. Promising solutions could be the combinations of Single Mode Fiber (SMF) and Dispersion Compensating Fiber (DCF), or Dispersion Shifted Fiber (DSF).

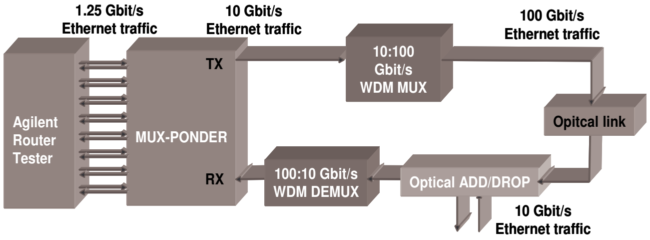


Fig. 12 100 Gb/s Ethernet WDM solution.

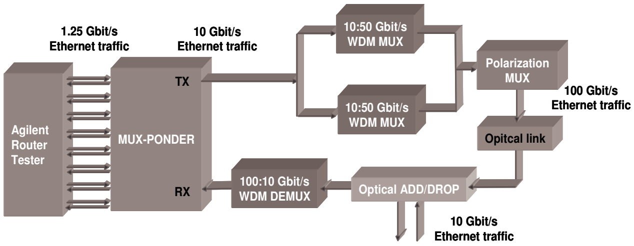


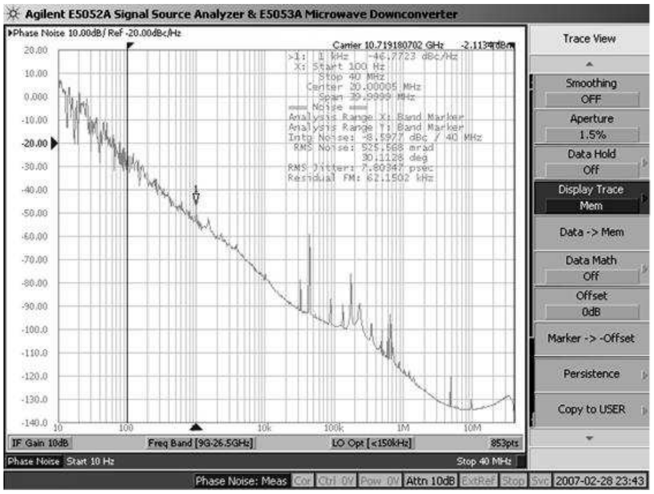
Fig. 13 100 Gb/s Ethernet WDM/Polarization solution.

V. RESULTS

Initially, the transmitter phase noise was measured using Agilent E5052 Signal Source Analyzer. Fig. 14 shows the timing jitter, measured in the range between 100 Hz and 40 MHz, for the MUX-Ponder as 7.8ps (RMS value). This value is good for a MUX-Ponder designed for 10 Gb/s Ethernet application. This MUX-Ponder is unsuitable for 100Gb/s Ethernet transmission and if required its phase noise would need to be significantly improved.

Preliminary results concerning 20 Gb/s OTDM-based Ethernet experiments are presented in order to validate the receiver functionalities.

In the implemented core testbed, depicted in Fig. 15, an EAM and 250 m-long HNLF span have been used for the clock generation and the pulsewidth compression respectively. As previously mentioned the NRZ-to-RZ conversion block and the optical demultiplexer have been both carried out exploiting XGM-nonlinear effect in semiconductor devices and a 10-to-20 OTDM MUX has been used in order to generate the 20 Gb/s Ethernet stream. In the realized scheme the ADD/DROP Multiplexer has not been used.



```
>1:  1 kHz   -46.7723 dBc/Hz
 X: Start 100 Hz
      Stop 40 MHz
    Center 20.00005 MHz
      Span 39.9999 MHz
=== Noise ===
Analysis Range X: Band Marker
Analysis Range Y: Band Marker
Intg Noise: -8.5977 dBc / 40 MHz
 RMS Noise: 525.568 mrad
            30.1128 deg
RMS Jitter: 7.80347 psec
Residual FM: 62.1502 kHz
```

Fig. 14 MUX-Ponder phase noisemeasurement exploited by means of an Agilent E5052 Signal Source Analyzer.

In these preliminary experiments propagation issues are not addressed and the 10 Gb/s de-multiplexed Ethernet stream is directly received by the MUX-Ponder.

The BER measurements for both tributary channels are shown in Fig. 16 together with the back-to-back (B2B) case. The curves show a penalty < 1 dB with a BER=10^{-9}.

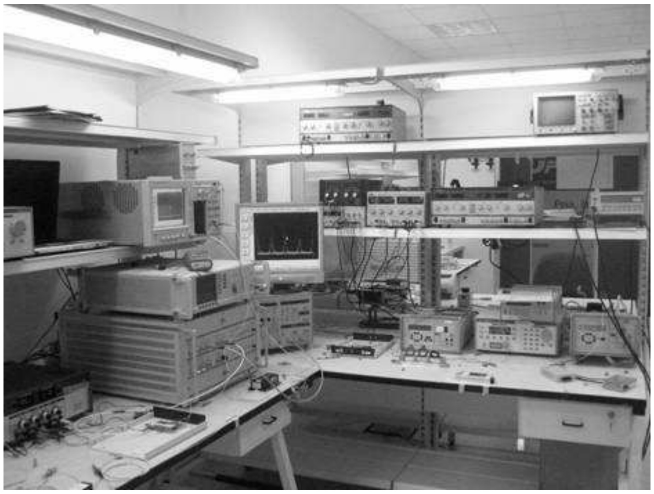


Fig. 15 Partial view of the implemented testbed.

In Fig. 17 the eye-diagrams of the 10 Gb/s RZ Ethernet signal and of the 100 Gb/s aggregated frame are shown. The future transmission experiments will be carried out using the proposed testbed and signal generation discussed in order to valuate 100 Gb/s Ethernet system performances and transmission impairments.

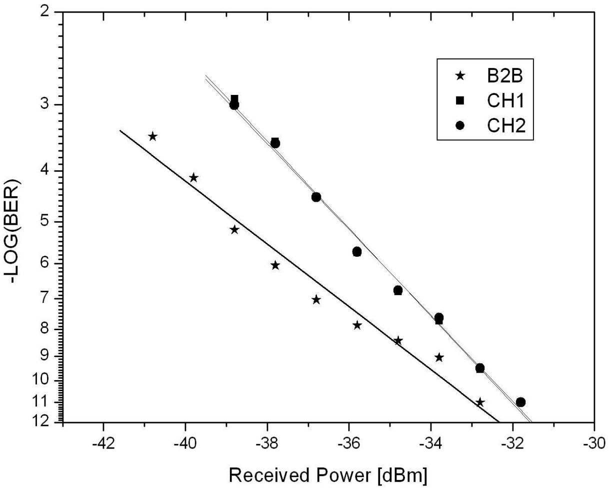
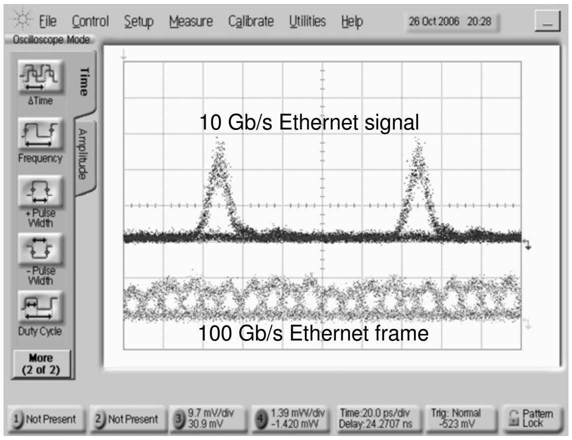


Fig. 16 BER curves in BtoB case and for both tributary channels of the 20 Gb/s Ethernet frame.



1 Not Present
2 Not Present
3 9.7 mV/div 30.9 mV
4 1.39 mW/div -1.420 mW
Time:20.0 ps/div Delay:24.2707 ns
Trig: Normal -523 mV

Fig. 17 Oscilloscope traces of the 10 Gb/s Ethernet signal and of the 100 Gb/s Ethernet aggregated frame.

VI. CONCLUSIONS

A complete testbed for investigating 100 Gb/s Ethernet implementations has been described. The testbed aims are to demonstrate the behavior of a complete Ethernet-based network operating at up to 100 Gb/s. In particular the objective is to investigate the challenges and the technical solutions required to obtain a complete 100 Gb/s Ethernet implementation compliant with the specifications being identified by the IEEE 802.3 Higher Speed Study Group. The target is to provide an adequate performance level to different critical network applications such as multimedia, Grid Computing etc at very high data rates. The testbed will also allow o investigation of transmission impairments experienced by the 100 Gb/s Ethernet optical signal over different types of optical fibers. The implementation of a preliminary OTDM solution operating at 20 Gb/s Ethernet has been demonstrated using the testbed.

ACKNOWLEDGMENT

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VII. REFERENCES

[1] Ethernet IEEE 802.3
[2] Fast Ethernet IEEE 802.3u
[3] Gigabit Ethernet IEEE 802.3z
[4] 10 Gigabit Ethernet IEEE 802.3ae
[5] IEEE 802.3 Higher Speed Study Group (HSSG), http://grouper.ieee.org/groups/802/3/hssg/public/index.html
[6] Kani, J. Teshima, M. Akimoto, K. Takachio, N. Suzuki, H. Iwatsuki, K. Ishii, M., "A WDM-based optical access network for wide-area gigabit access services", Communications Magazine, IEEE, February 2003.
[7] T. Swahn, J. Hallin, T. Kjellberg, C. Karnfelt, B.-E. Olsson, M. Andersson, H. Zirath, U. Mattsson, "OPTCOM – A 100 Gbit/s Tranceiver demonstrator project" Optillion AB c/o Chalmers University of Technologies, Sweden; Combitech Systems, Sweden.
[8] K. Murata, T. Enoki, H. Sugahara and M. Tokumitsu, "ICs for 100Gbps Data Transmission", K NTT Photonics Laboratories, 1th GAAS Symposium, Munich 2003.
[9] P.J. Winzer, G. Raybon, M. Duelk,"107-Gb/s Optical ETDM transmitter for 100G Ethernet transport", Bell Labs, Lucent Tachnologies, ECOC 2005.
[10] A. Zapata, M.Duser, J. Spencer, P. Bayvel, I. De Miguel, D. Breurer, N. Hanik, A. Gladish, "Next Generation 100Gigabit Metro Ethernet (100 GbME) using Multiwavelength Optical Rings", J. Lightwave Technology, November 2004.
[11] A.D. Ellis, C.W. Chow, "Serial OTDM for 100 Gbit Ethernet applications", Electronics Letters, April 2006.
[12] www.juniper.net
[13] www.agilent.com
[14] www.ericsson.com
[15] www.photrix.it
[16] St. Fischer, M. Dülk, E. Gamper, W. Vogt, W. Hunziker, E. Gini, H. Melchior, A. Buxens, H. N. Poulsen, and A. T. Clausen, "All-Optical Regenerative OTDM Add–Drop Multiplexing at 40 Gb/s Using Monolithic InP Mach–Zehnder Interferometer", IEEE Photon. Techn. Lett, vol.12, 3, pp. 335-337, 2000.
[17] C. Porzi, L. Potì, and A. Bogoni, "Novel Time Domain Add/Drop Multiplexer Based On Double-Pumped Four-Wave-Mixing and Cross-Phase-Modulation Induced Spectral Shift in a Semiconductor Optical Amplifier", OFC (2005), OThN1.
[18] J. Lee et al., Proc. OFC (2005), PDP23.
[19] L. Möller, Y. Su, X. Liu, J. Leuthold, and C. Xie, "Ultra high-speed optical phase correlated data signals," IEEE Photon Techn. Lett, vol.15, 11, pp. 1597-1599, 2003.