HDWDM UPGRADE OF CATV FIBRE-COAX NETWORKS FOR BROADBAND INTERACTIVE SERVICES

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Abstract: To introduce broadband interactive services in a fibre-coax CATV network with high splitting ratio, a HDWDM upgrading strategy in combination with conventional TDMA (or SCMA) techniques is presented. It features flexible network reconfiguration via wavelength reassignment at the optical network units. Key system item is a novel cost-effective bi-directional Erbium-doped fibre (/planar waveguide) amplifier handling simultaneously a high-grade analogue CATV downstream signal and multiwavelength interactive signals in a single fibre-coax network.

Introduction

Optical fibre is penetrating rapidly in subscriber access networks for distribution of CATV services. Today's CATV headend stations are feeding distributive services to large numbers of subscribers (>1000) in networks with abundant splitting both in the fibre part and in the coaxial part. Driven by the desire to provide interactive services via these networks as well, hybrid fibre-coax technologies have been developed offering basic interactive services like telephony and video-on-demand. However, there is also a strong drive towards interactive applications requiring more bandwidth, e.g., fast file transfer for teleworking and high-quality videotelephony. These services require upstream transport capacities in the order of 2 Mbit/s and more in such widely-split networks, which exceeds the limited addressing space and bandwidth of conventional TDMA (or SCMA) techniques. It would require broadband switching and concentration functions to be installed closer to the subscribers, thus affecting the network topology and complicating maintenance and operational aspects. The ACTS project TOBASCO (Towards Broadband Access Systems for CATV Optical networks) [1] is exploring ways to upgrade existing fibre-coax CATV networks. It is developing HDWDM techniques, by which the large subscriber group can be partitioned into smaller groups, each characterised by a specific wavelength. TDMA/SCMA techniques offering peak rates of more than 2 Mbit/s per subscriber (preferably on an ATM basis) can be used for addressing within these groups. Using these techniques, the switching functions for these interactive services are concentrated in the headend station, and the CATV network topology remains unchanged, both entailing significant techno-economic advantages.

In the present work we report on the system design, and focus on the design and performance of a novel cost-effective bi-directional optical amplifier for simultaneous amplification of a high-grade analogue CATV downstream signal and HDWDM up- and down-stream interactive signals.

System architecture

Fig. 1 shows a typical example of a highly-split fibre-coax CATV distribution network. Such systems are currently being installed, with split factors of up to N=8 and P=16 typically.

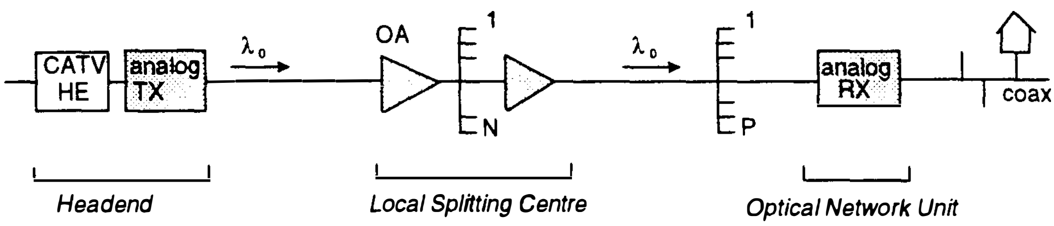

Fig. 1 Fibre-coax CATV distribution network

When introducing multiple wavelengths to carry the interactive services, wavelength routing can be employed in the Local Splitting Centre (LSC) to feed the separate groups of Optical Network Units (ONUs). An other option is to employ wavelength selection at the ONUs themselves. This option is explored in the TOBASCO project, and is shown in Fig. 2. It enables network reconfiguration without having to intrude the outside fibre plant: an other wavelength can be assigned to an ONU by switching it to that wavelength. Via the Network Management and Control subsystem, the network operator is in control of the network configuration, and he can adapt it easily when requested without touching the physical topology, as illustrated by Fig. 3. Thus the capacity available to an ONU can be adjusted upon demand; excess traffic load can be shifted to an other wavelength which has still spare capacity. Moreover, an ONU does not necessarily have to receive and to send on the same wavelength. Fig. 4 exemplifies how an ONU may choose for upstream transmission a wavelength different from that for downstream transmission. Thus the virtual upstream network topology may differ from the downstream one, which may be useful for highly asymmetric services. By optimising the wavelength allocation at the ONUs, the network operator is able to adapt the network configuration to the amount of asymmetry of the services offered.

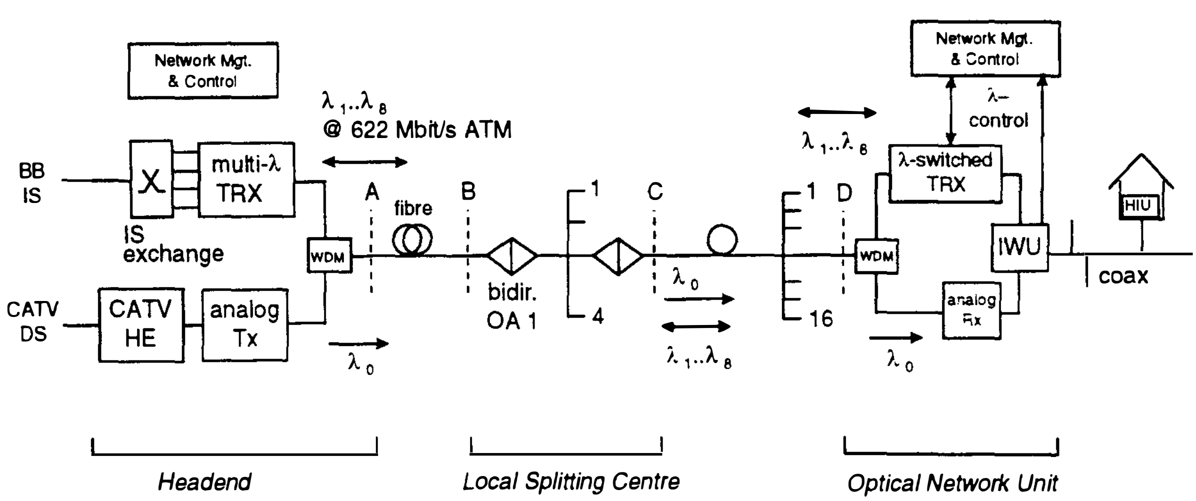

Fig. 2 Flexible upgrade to broadband interactive services by wavelength switching at the ONUs

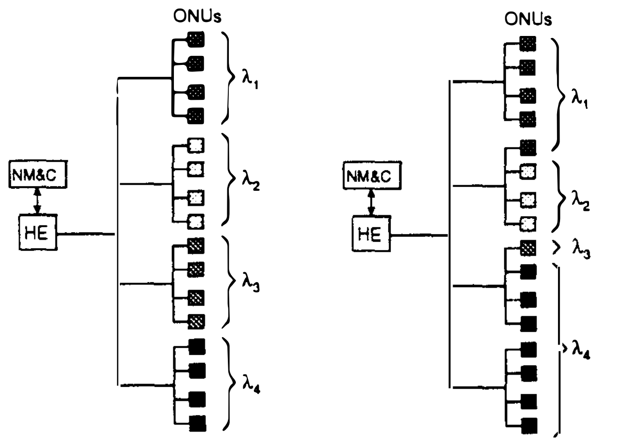

Fig. 3 Network reconfiguration on a wavelength basis

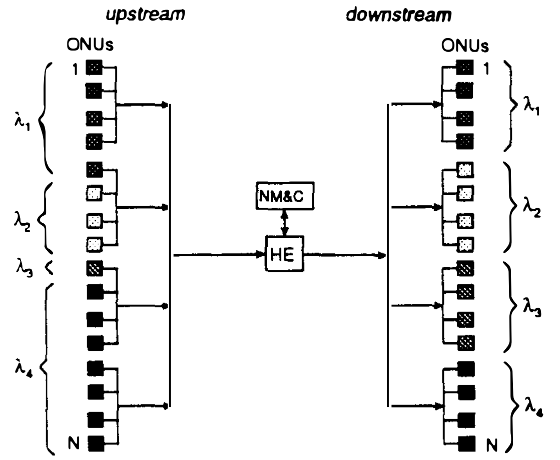

Fig. 4 Decoupling of up- and down-stream topology

In the outside fibre plant, upgrading from the pure distribution network in Fig. 1 to the broadband network in Fig. 2 requires only replacement of the unidirectional optical amplifiers by bi-directional ones. Also a gradual upgrading of the ONUs is feasible: only those ONUs that need (adjustable) upstream capacity have to be equipped with wavelength-switchable transceivers. At other ONUs, a single-wavelength transceiver will suffice, or, when only distributive services are requested, even only the CATV analog receiver preceeded by an optical filter blocking the wavelengths carrying the interactive services.

The wavelength-switched transceiver in the ONU consists of an array of laser diodes and photodiodes, partly integrated with wavelength (de)multiplexing functions. Using arrays instead of tunable devices allows setting up a new wavelength path and the corresponding network control parameters before breaking down the old one; this yields a minimal disruption of services. Furthermore, it offers transmitter and receiver redundancy at the ONU and at the headend. In the fibre part of the network, each wavelength carries 622 Mbit/s data streams in ATM format. Four wavelengths are used for downstream transmission of the interactive signals, and four for upstream. To reduce reflection-induced crosstalk, the up- and down-stream wavelengths are interleaved with a spacing of 100 GHz, and are positioned in the 1535-1541 nm range as illustrated by Fig. 5. The launched power per

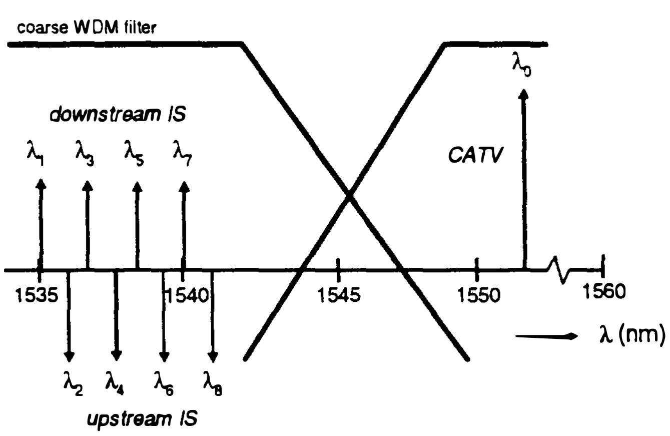

Fig.5 Wavelength allocation

wavelength is -8 dBm at headend interface A and ONU interface D; the received power at A and D is -16 dBm. The analogue CATV signal is positioned in the 1550-1560 nm range, the optimum range for low-noise, high-power erbium-doped fibre amplifiers. In the Interworking Unit (IWU) in the ONU, the ATM format is translated into Ethernet, thus providing via the Home Interface Unit (HIU) a readily available interface with PC-based teleworkers. The IWU also takes care of fitting the interactive services into the spectral bands free in the CATV spectrum on the coaxial bus network. The spectrum for the upstream signals will be positioned below 30 MHz. In the order of 50 living units are to be served by a single ONU, offering an analogue CATV signal and an interface for digital interactive services up to 10 Mbit/s downstream and 2 Mbit/s upstream to each of them. Thus in total up to 3200 households can be provided with broadband interactive services by a single headend system.

Bi-directional optical amplifiers

The requirements on the optical amplifiers in the TOBASCO system are quite diverse:

- the analogue CATV distributive signal (DS) has to be boosted up to high power (typ. +13 dBm), with a low noise figure, in the downstream direction
- the digital multi-wavelength interactive signals (IS) have to be amplified without mutual crosscoupling, with a gain independent of wavelength, irrespective of their bursty ATM-cell nature, in two directions. In particular when rearranging the upstream wavelengths of the ONUs, as exemplified in Figs. 3 and 4, as well as due to bursty ATM traffic, the input powers of the second-stage amplifiers may fluctuate considerably.

Optimising a conventional fibre amplifier for both applications simultaneously leads to a compromise for the length of the erbium-doped fibre (EDF). The high output power requirement for DS requires a relatively long length of EDF; for the IS signals, however, the flatness of the gain curves versus wavelength and input power, the negligible crosscoupling and the low noise figure require a short EDF driven into high inversion. Therefore we have segmented the amplifier in two sections: one handling the DS signal. and the other the IS signals.

Regarding the IS signals, the cascading of amplifiers in a split network leads to a strong accumulation of the amplified spontaneous emission (ASE) noise in the upstream direction, whereas the noise accumulation in downstream direction is much less as will be shown next. Assuming loss factors α_f of the fibre link between the headend and the LSC, α_1 of the $1:N$ splitter inside the LSC. and α_2 of the fibre plus the splitter between the LSC and an ONU, a gain factor G_1 and upstream (downstream) $ASE_{1.u}$ ($ASE_{1.d}$) of the shared optical amplifier in the LSC, and G_2 and $ASE_{2.u}$ ($ASE_{2.d}$) of the second stage amplifiers, the upstream ASE_u arriving at the headend is

$$ASE_u = \alpha_f ASE_{1,u} + \alpha_f G_1 \alpha_1 \sum_{i=1}^{N} ASE_{2u,i} = \alpha_f \left(ASE_{1,u} + \varepsilon G_1 ASE_{2,u}\right)$$

and the downstream ASE_d for the interactive wavelengths arriving at the ONU is

$$ASE_d = \alpha_2 ASE_{2.d} + \alpha_2 \alpha_1 G_2 ASE_{1.d} = ASE_{1.d} / G_1 + \alpha_2 ASE_{2.d}$$

where the splitter inside the LSC is assumed to have an excess loss factor ε ($=\alpha_1 \cdot N = 1$), and G_1 together with G_2 compensate for the splitting losses of both splitting stages as well as the losses of the fibre drop to the ONU (i.e., $G_1 \cdot \alpha_1 \cdot G_2 \cdot \alpha_2 = 1$). The insertion losses of the LSC 1:4 splitter and the in-field 1:16 splitter are about 7 dB and 13 dB, respectively, and the feeder fibre is assumed to have a length up to 20 km at 0.4 dB/km. At the transmit and receive power levels quoted before, the amplifiers jointly have to provide 20 dB of gain up- and downstream for each IS wavelength. As shown by the calculation, ASE_u/α_f is much larger than ASE_d, and is dominated by $G_1 \cdot ASE_{2,u}$. Therefore the second stage amplifier has to be designed for low ASE, while $G_1 \cdot ASE_{2,u}$ should be small. In order to arrive at identical amplifier modules throughout the system, it has been chosen to take $G_1 = G_2 = 10$ dB.

Alternatively, one may consider to concentrate the total IS gain in Fig. 2 in one amplifier, i.e. to shift the gain of the second stage amplifiers into the shared amplifier placed before the LSC splitter. This will, in general, imply an increased noise figure of the amplifier. It can be shown that, in comparison to the separate amplifier stages, the overall noise figure does not deteriorate provided that the total gain is less than $(1/(1-\varepsilon))^2$, while assuming an identical flat gain spectrum for all amplifiers. For a splitter excess loss of 0.5 dB. $\varepsilon = 0.9$ and thus for a total gain around 20 dB one may consider the use of a single amplifier. The TOBASCO network indeed requires such a total gain figure. However, adopting this single IS amplifier solution, while maintaining multiple DS amplifiers, requires an extra pump laser in the shared amplifier and two different types of optical amplifiers, which in general leads to an increased cost. In addition, the IS gain flatness will deteriorate because of the required gain increase.

Taking the above considerations into account, we propose a new concept for the amplifier architecture, which comprises two amplifying sections, and is shown in Fig. 6. A similar concept, but for only two wavelength signals, has been demonstrated by us before [2]. The two sections are separated by a coarse WDM splitter, in accordance with the wavelength allocation of Fig. 5. One amplifying section is optimised for the downstream analogue CATV signal, located in the range 1550-1560 nm. It yields an output power of +13 dBm, an absolute gain slope of <0.2 dB/nm, and an overall noise figure below 5.5 dB. It contains a 30 dB optical isolator to prevent multiple path reflection-induced increase of the relative intensity noise (RIN). The optimum EDF length is 12 metres. The other amplifying section for the interactive signals has been designed for optimum gain flatness versus wavelength and input power variations. The optimum EDF length for this section is 5 metres, yielding the required gain of 10 dB. A single 980 nm 110 mW pump laser diode is used; 65% of its power is used for co-propagating pumping the CATV amplifying section, and 35% for pumping the interactive signals amplifying section.

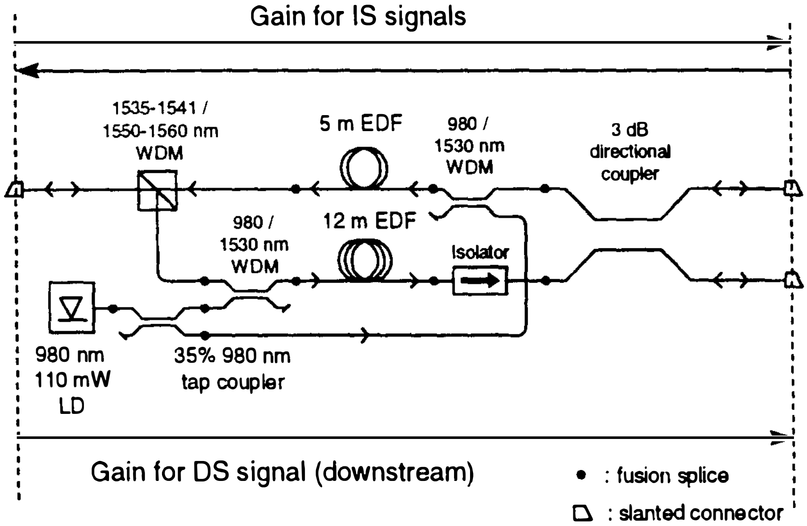

Fig. 6 Two-window optical fibre amplifier

Using the EDFA modelling theory of Giles [3], an analysis has been made of the gain and noise behaviour of amplifiers with a short highly-inverted EDF. Fig. 7 shows the characteristics of a 5 metres long EDF section, for the 8 interactive wavelengths in the TOBASCO system (downstream 1535.3, 1536.9, 1538.5, 1540.1 nm; upstream 1536.1, 1537.7 , 1539.3, 1540.9 nm). It can be observed that for the expected input powers ranging from -30 to -20 dBm, the gain is 10±1 dB. The noise figure actually is below 3 dB, which is equivalent to low ASE levels. Noise figures (*NF*) below 3 dB can occur for low-gain, highly inverted EDFs, since by definition

$$NF = SNR_{in} / SNR_{out} = 2 \cdot \frac{G-1}{G} \cdot \left(1 + \frac{1}{\eta} + \frac{1}{\eta n_2}\right)^{-1}$$

with $\eta = g^*/\alpha$, where g^* is the emission coefficient, and α the absorption coefficient, n_2 the average Erbium ion inversion level, and G the total (linear) gain. Since the EDF in the present amplifier design is short, we have $n_2 = 0.98$ for most input situations. Also, around 1535 nm, $\eta = 1$, and with $G = 10$, these conditions easily lead to sub 3 dB noise figures. If we try to amplify the IS channels in the presence of the strong DS signal in the same EDF, the longer EDF length required causes reduction of inversion leading to an increase in noise figure, as can be seen in Fig. 7. In the TOBASCO project, glass-integrated planar Er/Yb-doped waveguide amplifiers with a short active waveguide section followed by a splitter section are studied for the bidirectional amplification of the multiwavelength, yielding a low-cost lossless splitter implementation [4]. A first sample shows measured gain characteristics given in Fig. 8. With respect to the flatness of the gain-vs.-input power curves, these results compare well with the results found for the fibre amplifier in Fig. 7. Work is going on to improve the gain and its flatness versus wavelength.

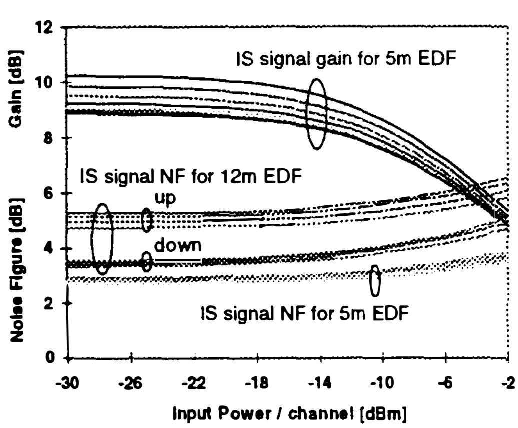

Fig. 7 Gain and Noise Figure versus input power per wavelength channel for two lengths of erbium-doped fibre (8 channels in use; for 12 m data also CATV signal present)

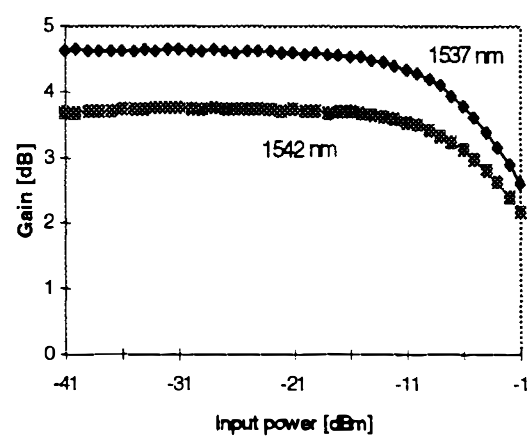

Fig. 8 Measured characteristics of integrated planar optical amplifier (110 mW 980 nm pump)

Based on this, the two-window amplifier of Fig. 6 can be laid out cost-effectively as a hybrid assembly of an Er/Yb planar waveguide amplifier for the interactive multiwavelength signals, and an Er-doped fibre plus isolator for the distributive analog CATV signal. Fig. 9 shows the design, featuring 980 nm pump laser redundancy and 1:8 splitting by integrated planar waveguide splitters.

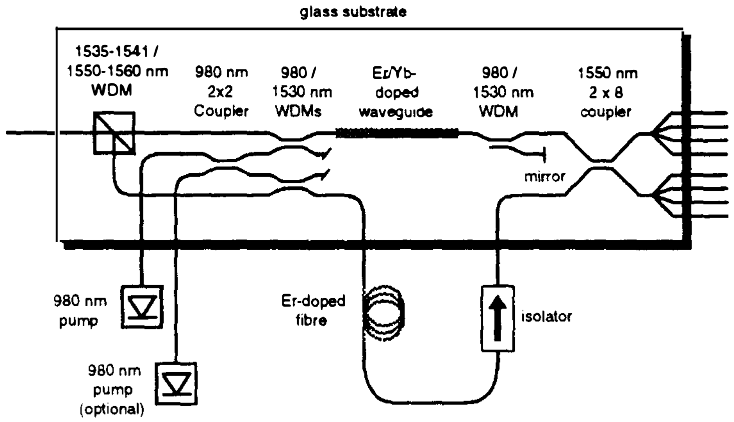

Fig. 9 Hybrid two-window optical branching amplifier

Conclusions

A system to provide broadband interactive services on a highly-split fibre-coax CATV network has been presented, employing HDWDM techniques to achieve high network split ratios. It features flexible network reconfiguration by wavelength reassignment at the optical network units. A new bi-directional optical amplifier design (all-fibre, or hybrid fibre/planar waveguide) shows optimum performance for both boosting of the CATV signal power and the low-noise low-crosstalk amplification of the multiwavelength interactive signals.

Acknowledgements

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