Ignacio González Insua

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Optical generation of mm-wave signals for use in broadband radio over fiber systems

Ignacio González Insua

von der Fakultät Elektrotechnik und Informationstechnik der Technischen Universität Dresden

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Constants

c	Light speed in vacuum	$299.79 \cdot 10^{6}$ m/s
h	Planck's constant	$6.62 \cdot 10^{-34}$ Ws^2
k_B	Boltzmann constant	$1.3807 \cdot 10^{-23}$ J/K
π	pi	3.1416
q	Electron charge	$1.6022 \cdot 10^{-19}$ As

Symbols

α	Fiber loss parameter
α_{eff}	Effective α-factor
α_{int}	SOA internal loss
α_{LE}	Linewidth enhancement factor
α_{MZM}	Chirp parameter of a Mach Zehnder modulator
a_0	Average optical intensity
β	Propagation constant
B	Bandwidth
B_n	Noise bandwidth
β_2	Group velocity dispersion parameter
B_j	Oscillator strength
C	Channel capacity
C/N_{pen}	Carrier to noise penalty
CS_{el}	Electrical carrier suppression
CS_{opt}	Optical carrier suppression
d	Distance (general)
d_0	Reference distance
δ	Dirac impulse
D	Dispersion parameter
D_M	Material dispersion
D_W	Waveguide dispersion
Δf	Frequency separation
$\Delta\phi$	Optical phase difference
$\Delta\phi_{FM,IM}$	Phase offset between frequency and intensity modulation
Δg	Gain variation
ΔL	Length difference
ΔL_0	Repetition length of transmission zeros
ΔL_{path}	Optical path length difference
Δn	Birefringence index
ΔP	Power variation
$\Delta\theta$	Electrical phase difference
ΔT	Pulse broadening
ΔT_N	Normalized pulse broadening
$\Delta\lambda$	Wavelength spectral width
$\Delta\tau$	Differential propagation delay
$\Delta\tau_{disp}$	Dispersion induced differential propagation delay
$\Delta\tau_{path}$	Path difference induced differential propagation delay

$\Delta\tau_{pmd}$	Polarization mode dispersion induced differential propagation delay
$\Delta\nu$	Signal linewidth (general)
$\Delta\omega$	Pulse spectral width
E	Electric field (general)
ER	Extinction ratio
ER_{pen}	Extinction ratio penalty
E_{sat}	Saturation energy in a SOA
f	Frequency (general)
f_c	Optical carrier frequency
f_{IF}	Intermediate frequency
f_{LO}	Local oscillator frequency
f_m	Modulation frequency
f_{opt}	Optical frequency
f_{RF}	RF frequency
FSR	Free spectral range
Γ	Mode confinement
Γ_n	n^{th} harmonic mixer conversion gain
G	Gain (general)
g_0	SOA gain per unit length
G_C	Combined antenna gain
G_{RX}	Receiver antenna gain
G_{TX}	Transmitter antenna gain
$H(f)$	Fiber low pass equivalent transfer function
η	Photodiode quantum efficiency
η_{conv}	Wavelength conversion efficiency
I	Current (general)
I_0	Mean pulse amplitude for a logical “zero”
I_1	Mean pulse amplitude for a logical “one”
I_{bias}	Bias current
I_d	Dark current
i_s	Shot noise current
i_T	Thermal noise current
IL	Implementation loss
φ	Phase (general)
Φ_k	Random phase
J	Current density
J_k	Bessel function of the k^{th} order
φ_d	Dispersion induced phase change
κ	Coupler splitting ratio
κ_{pol}	Polarization splitting ratio
λ	Wavelength (general)
λ_0	Zero dispersion wavelength
L	Length (general)
L_0	First transmission zero length
l_c	Coherence length
L_{shad}	Shadowing loss

LL	Link loss
m_a	Amplitude modulation index
m_f	Frequency modulation index
m_{ph}	Phase modulation index
n	Refraction index
N_{cd}	Carrier density in a SOA
n_{cd}	Carrier density perturbation
n_g	Group index
n_L	Refraction index in a laser cavity
n_p	Peak number of photons required per bit of information
n_{path}	Path loss exponent
n_{sp}	Spontaneous emission inversion paramater
$n_{x,y}$	Polarisation dependent refraction index
N_{power}	Noise power
NF_{amp}	Amplifier noise figure
NF_{RX}	Receiver noise figure
P_{el}	Electrical power (general)
P_{LO}	Local oscillator optical power
P_{opt}	Optical power (general)
P_{probe}	Probe optical power
P_{pump}	Pump optical power
P_s	Signal optical power
P_{sat}	SOA saturation power
Π	Instantaneous optical power
$PIIN$	Phase induced intensity noise
PL	Path loss
$PL_{freespace}$	Path loss in free space
P_{RX}	Received RF power
P_{TX}	Transmitted RF power
Q	Q factor
θ	Angle between the signal linearized polarization state and *x* polarization axis
R	Photodiode responsivity
r_{33}	Pockels coefficient
R_b	Bit rate
R_L	Load resistor
RIN	Relative intensity noise
S	Dispersion slope
SE	Spectral efficiency
SL	System loss factor
SNR	Signal to Noise Ratio
$S_f(f)$	Laser frequency fluctuation spectrum
$S_\phi(f)$	Phase fluctuation spectrum
σ_0	Standard deviation for a logical “zero”
σ_1	Standard deviation for a logical “one”
σ_n	Noise standard deviation
σ^2_s	Shot noise variance

σ^2_T	Thermal noise variance
σ^2_ϕ	Phase noise variance
T	Temperature (general)
T_b	Bit slot time
tr	Rise/fall time at transmitter
T_s	Received rise/fall time
t	time (general)
t_m	Transmission factor
τ	Time delay
τ_c	Carrier lifetime
τ_s	Stimulated carrier lifetime
V	Voltage (general)
V_b	Bias voltage
V_{DC}	DC bias voltage
V_o	Offset voltage
V_π	Half-wave voltage
v_g	Group velocity
ω	Angular frequency
ω_j	Resonance angular frequency
Z_t	Overall transceiver impedance

Operators

j	Imaginy unit
x^*	Complex conjugation of x

Acronyms

10 GET	10 Gigabit Ethernet
ASE	Amplified Spontaneous Emission
ASK	Amplitude Shift Keying
A/V	Audio/video
AWGN	Additive White Gaussian Noise
BtB-Measurement	Back-to-Back-Measurement (Reference measurement for Bit Error Rate)
BER	Bit Error Rate
BERT	Bit Error Rate Tester
BiCMOS	Bipolar Complementary Metal Oxide Semiconductor
BPSK	Binary Phase Shift Keying
BS	Base Station
CATV	Community Antenna TeleVision
Ccw	Counter clockwise
CD	Chromatic Dispersion
C/N	Carrier to Noise
CR	Coupling Ratio
CS	Central Station
CS_{el}	Electrical Carrier Suppression
CS_{opt}	Optical Carrier Suppression

CMOS	Complementary Metal Oxide Semiconductor
CW	Continuous Wave
Cw	Clockwise
DCF	Dispersion Compensating Fiber
DFB	Distributed Feedback Laser
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSB-SC	Double Sideband with Suppressed Carrier
DSF	Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplex
EAM	Electro-Absorption Modulator
EAT	Electro-Absorption Transceiver
EBPF	Electrical BandPass Filter
ECL	External Cavity Laser
EDFA	Erbium Doped Fiber Amplifier
ELPF	Electrical Low Pass Filter
E/O	Electrical to Optical
ER	Extinction Ratio
ESA	Electrical Spectrum Analyzer
FBG	Fiber Bragg Grating
FDM	Frequency Division Multiplex
FLM	Fiber Loop Mirror
FM	Frequency Modulation
FSK	Frequency Shift Keying
FSR	Free spectral range
FTTH	Fiber to the Home
GaAs	Gallium Arsenide
GVD	Group Velocity Dispersion
HBT	Heterojunction Bipolar Transistor
HDTV	High Definition Television
HEMT	High Electron Mobility Transistor
IC	Integrated Circuit
IF	Intermediate Frequency
IL	Insertion Loss
IM	Intensity Modulation
IM/DD	Intensity Modulation / Direct Detection
InP	Indium Phoshipe
ISI	InterSymbol Interference
ITU	International Telecommunication Union
LAN	Local area network
LD	Laser Diode
LFS	Linear Fit Slope
$LiNbO_3$	Lithium Niobate
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line Of Sight
LPF	Low Pass Filter

MAX	MAXimum transmission bias point
MIN	MINimum transmission bias point
MMF	Multi Mode Fiber
MZI	Mach-Zehnder Interferometer
MZM	Mach-Zehnder Modulator
NLOS	Non Line Of Sight
NRZ-Format	Non-Return-to-Zero-Format
OBPF	Optical BandPass Filter
ODSB	Optical Double SideBand
O/E	Optical to Electrical
OFDM	Orthogonal Frequency Division Multiplex
ONU	Optical Network Unit
OOK	On-Off Keying
OSA	Optical Spectrum Analyzer
OSSB	Optical Single SideBand
PC	Polarization Controller
PD	Photodiode
PIIN	Phase Induced Intensity Noise
PLL	Phase Locked Loop
PM	Phase Modulation/Modulator
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
PRBS	Pseudorandom Binary Sequence
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QCSE	Quantum Confined Stark Effect
QPSK	Quadrature Phase Shift Keying
QUAD	QUADrature transmission bias point
RBW	Resolution BandWidth
RF	Radio Frequency
RHD	Remote Heteroyne Detection
RoF	Radio over Fiber
RSOA	Reflective Semiconductor Optical Amplifier
SiGe	Silicon Germanium
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SOA	Semiconductor Optical Amplifier
SSB	Single SideBand
UWB	Ultra WideBand
VCO	Voltage Controlled Oscillator
xDSL	Digital Subscriber Line
XGM	Cross Gain Modulation
XPM	Cross Phase Modulation
WDM	Wavelength Division Multiplex
WLAN	Wireless local area network
WPAN	Wireless personal area network

1 Introduction

The demand for high data rates seems to keep growing as the integration of many services like internet telephony, high-definition TV (HDTV), audio/video (A/V) on demand, etc. push the existing connections bandwidth limits. Moreover, the end user would also like to access all these services while being mobile.

Commercial xDSL service providers offer peak data rates up to 50 Mbps (e.g. VDSL) to the end user and gigabit wired connections will be available in the near future. Nonetheless, there is a limit as to how much bandwidth can be transported over a twisted pair copper wire due to its low frequency cut-off. Therefore complex modulation schemes such as orthogonal frequency division multiplexing (OFDM) are used which require intensive digital post processing. While this modulation scheme is the principal driving force for xDSL services and the most popular one used up to date, the data rates are still not high enough to provide all the afore mentioned services with decent quality.

Fiber to the home (FTTH) is an emerging technology which offers the enormous bandwidth of optical fiber (in the THz range). Connections are being deployed in many countries (in USA by Verizon, in Germany by Deutsche Telekom, in France by France Telecom, etc) and future networks start looking as shown in Figure 1.1. The connection between the optical line terminal and the end user will be carried out through a passive optical network (PON) to provide broadband coverage of broadcast TV, internet traffic and public switched telephone network traffic (PSTN).

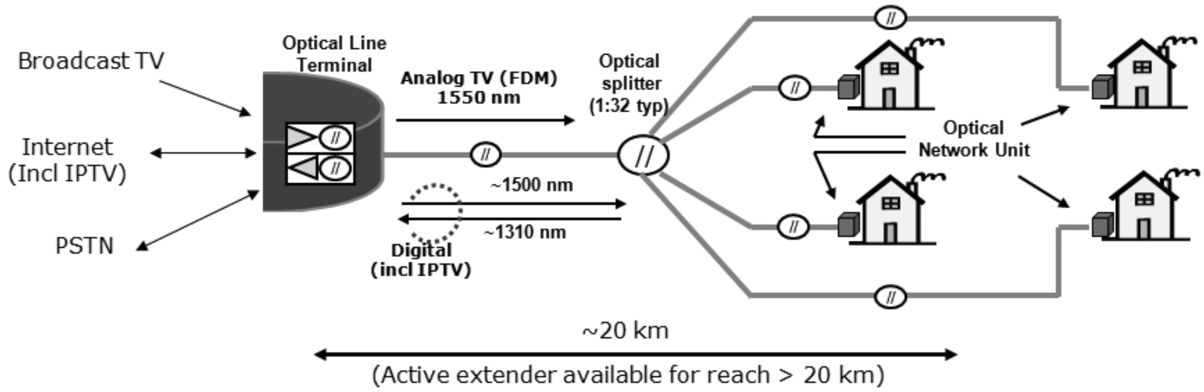

Figure 1.1: FTTH network architecture. FDM: Frequency Division Multiplex [1].

Each house will have an optical network unit (ONU) capable of routing all the traffic and distributing it inside the household. A typical home with a FTTH connection will appear as shown in Figure 1.2. The huge bandwidth can be then divided into the different users (i.e. rooms) in the house and be transported through low loss, electromagnetic immune optical fiber. Wired gigabit connections will be easily implemented such as already deployed 10 Gigabit Ethernet (10 GET) but that leaves the wireless transmission problem still unsolved for mobile devices.

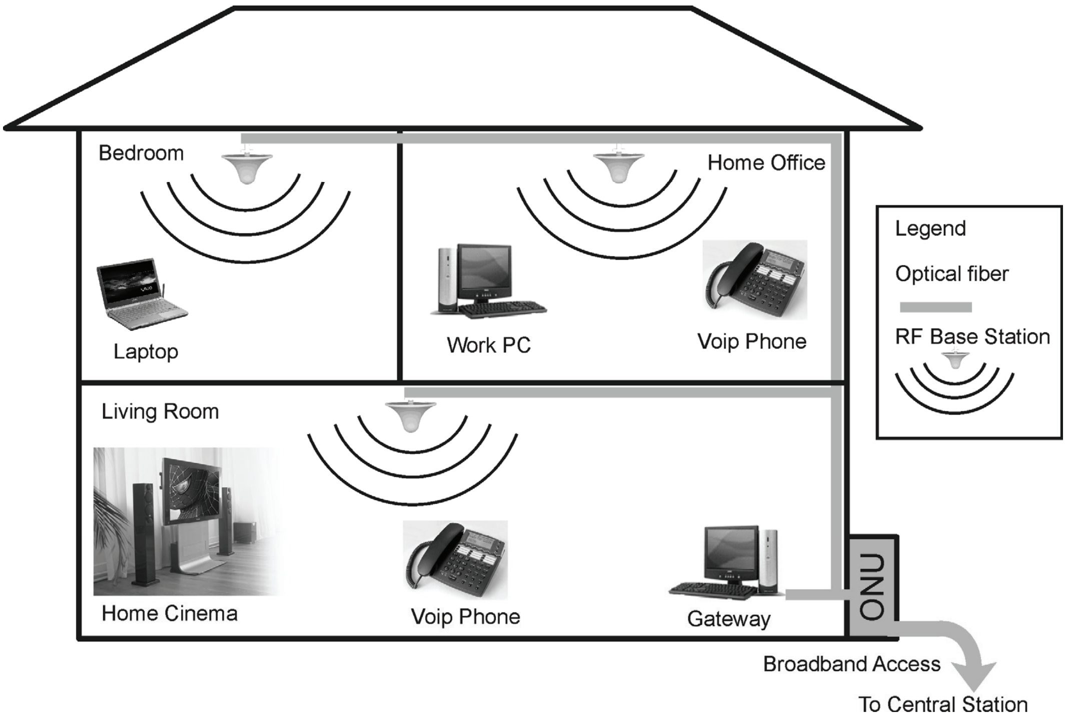

Figure 1.2: FTTH inhouse distribution. ONU: Optical network unit.

Millimeter wave Radio-over-Fiber (RoF) systems are a key enabler to realize gigabit speed broadband wireless services as there is a huge unlicensed bandwidth at these high frequencies (i.e. 60 GHz, 70 GHz and 90 GHz). The idea behind RoF systems is to centralize all the expensive components and control devices in the so called central station (CS) so as to simplify the distribution points, called base stations (BS), which are fed through optical fiber as seen in Figure 1.3. The enormous bandwidth offered by optical fiber allows the division of space in picocells or femtocells, depending on the cell size. Within each cell, a BS is in charge of distributing the data among its users through different intermediate frequencies. There are various proposed architectures, such as RoF without mm-wave generation, with sub mm-wave generation or with mm-wave generation (the special case depicted in Figure 1.3), which will be discussed later. The BS is then an optical to electrical (O/E) converter which sends the broadband data on a mm-wave carrier and depending on the RoF architecture, is more or less complex. In this context, each base station (or in FTTH case, each room in the household) will have a small, compact and most importantly cheap O/E transceiver which would be connected via optical fiber to the central station via an optical network.

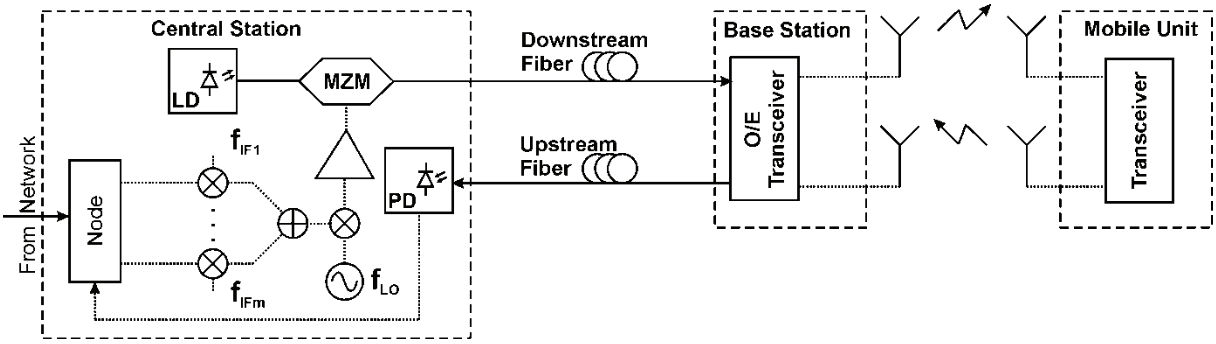

Figure 1.3: RoF basic architecture.

Moreover, future research concentrates on going one step further and giving up on the CS altogether by using directly the wired 10 GET connection in the household and a simple scheme to upconvert the broadband baseband signal. A simple solution would be to remotely heterodyne the 10 GET optical signal with a local oscillator separated by the desired mm-wave frequency. The critical system parameters as well as optimum receivers need to be further investigated for this application.

However, today the architecture of RoF systems is completely different and not compatible with FTTH architectures. In future access networks like wavelength division multiplex passive optical networks (WDM-PON) analog RoF and digital FTTH signals must co-exist in the same fiber infrastructure. If this will happen, seamless broadband access services could be readily put into the field. In the second generation FTTH system splitting ratio up to 1:64 (or even more) and fiber lengths greater than 50 km are under discussion. Moreover, the bit error rate (BER) requirements are as high as BER = 10^{-9}, either for wired or wireless systems. This results in rather high values for the power budget of the analog RoF systems and a good immunity against the chromatic dispersion of the fiber.

The outline of this work is as follows. Chapter 2 will discuss the requirements for broadband wireless access services in terms of channel capacity, free space propagation and fading effects while also taking into account the most important technical challenges still ahead.

Chapter 3 gives an overview of the most common optical mm-wave generation methods whereas chapter 4 discusses the effects of the different RoF architectures with regard to propagation in a dispersive medium (i.e. optical fiber) and the penalties incurred therein. Chapter 5 first characterizes the generation of mm-wave signals with a Mach-Zehnder modulator under different conditions. Moreover, a novel generation method via an optical fiber loop mirror with different configurations is proposed and is one of the main topics of this thesis. In chapter 6 an evaluation of the different receiver architectures for the mobile unit is developed, taking special interest in sensitivity, implementation loss and bit error rate performance for the different setups. The maximum attainable capacities of each receiver are also calculated. In chapter 7 the results of the broadband wireless experiments are presented and discussed in detail. Finally, chapter 8 provides a summary of the most important results achieved throughout this work.