1. Introduction

Space communication already plays a significant role in making our global network as widespread as it is today. Worldwide live broadcasting of popular events or communication with users located in remote areas relies on satellite communication. Todays communication systems in space make use of radio frequency (RF) technologies to transmit data. However, even if there is still some room to push microwave technologies to better performances, eventually the performance of these systems will be limited due to their relatively large wavelength. The ever increasing demand for higher data rate and thus higher bandwidth will force scientists and engineers to look for new technologies to fulfill these needs. Optical data links are considered to be the next generation space communication links not only because of their capability to provide higher data rates but also because they offer numerous other advantages like a reduced antenna size (discussed in more detail in chapter 2.1.1).

The most promising optical communication format in space is considered to be coherent optical communication. The feasibility of a coherent optical data link with GB/s data rates in space has already been demonstrated between the German satellite TerraSAR-X and the US satellite NFIRE [1].

An optical communication network in space as it may look like in the future is depicted in fig. 1.1. Satellite to satellite as well as satellite to ground communication links will be realized in order to establish a widely ramified communication network. However, the research on coherent optical communication in space is still at the beginning and several challenges are to be faced.

TESAT, the company that manufactured the laser communication terminals (LCT) utilized in the above mentioned satellites, uses optically pumped solid state lasers to obtain the required spectral stability and linewidth. However, these lasers suffer from low efficiency, poor mechanical stability, large size, and heavy weight. In contrast, semiconductor lasers do not exhibit these drawbacks. Moreover, semiconductor lasers cover most of the visible and NIR spectral range which can further be extended by frequency-doubling. Furthermore, semiconductor lasers feature direct high bandwidth modulation capability. However, the requirements for coherent optical LCTs in terms of spectral stability and linewidth have not been met so far by high power semiconductor lasers.

There are already attempts towards the miniaturization of LCTs. One example is the "European Space Agency" (ESA) project SOTT (small optical user terminal) where the focus lies on the realization of low weight, low cost, and efficient laser terminals. In the future ESA plans to further fund projects related to the miniaturization of LCTs under the ARTES (advanced research in telecommunication systems) program [2].

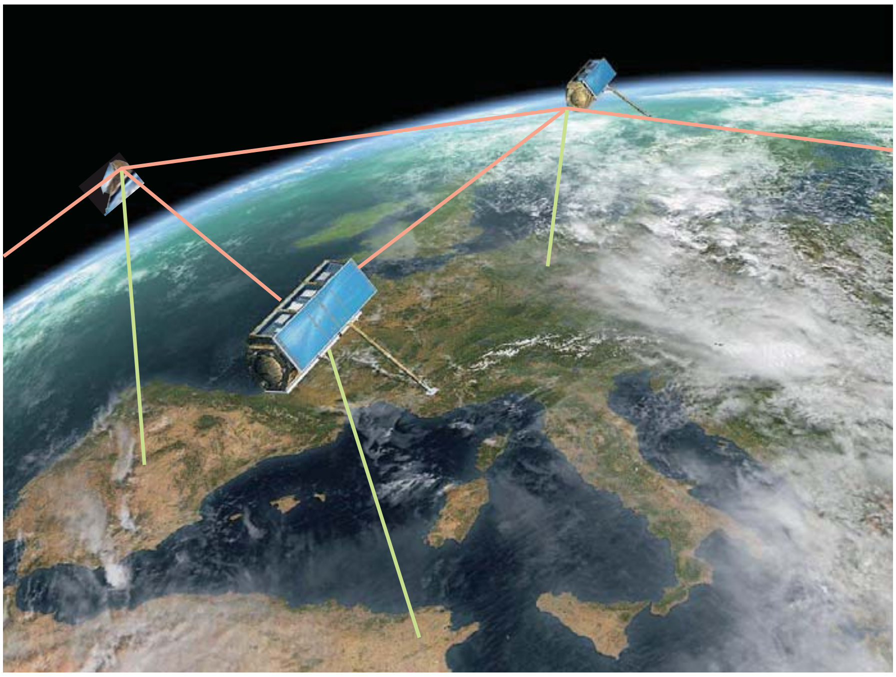

Figure 1.1.: An optical communication network realized in space as it may look like in the future. Satellite-satellite communication indicated with reddish lines, satellite-ground communication with greenish lines. Image courtesy: "Deutsches Zentrum für Luft- und Raumfahrt e. V. DLR" (data links were added).

In the long run, a widespread coherent optical communication network will require a large number of LCTs in space. Since semiconductor lasers feature the smallest volume, potentially the lowest cost, and the highest efficiency of all laser sources, miniaturization and optimization of energy efficiency are the points where semiconductor lasers will make the difference. Now is therefore the right time to develop semiconductor-based laser sources that will meet the specifications for coherent space communication in order to be ready when the market demands for such solutions.

2. Narrow Linewidth Semiconductor Lasers and Their Applications

This chapter gives an introduction to the developments in the field of narrow linewidth semiconductor lasers as well as to potential applications like coherent optical free-space communication.

2.1. Applications of Narrow Linewidth Semiconductor Lasers

If the spectral stability requirements can be met, semiconductor lasers would be ideal candidates as laser sources for coherent optical free-space communication. Therefore, this application and its requirements will be discussed in more detail. Furthermore, possible applications in the field of precision measurements will briefly be presented.

2.1.1. Coherent Optical free-space Communication

In contrast to conventional RF communication systems, the carrier frequency of an optical communication system is significantly smaller (optical: $\approx 1\,\mu\text{m}$, RF: $\approx 10\,\text{cm}$).

In general a communication link with a higher carrier frequency allows the transmission of higher data rates. Moreover, the smaller wavelength significantly reduces the size of the communication cone through a better focusing of the beam and further reduces the size of the antenna. In contrast to RF communication, generally only one beam is reaching the receiver in an optical data link and hence no interference problems occur. Furthermore, optical data links are considered to be tap-proof because monitoring of the signal can only be accomplished by interrupting the link or by placing a receiver close to the transmission cone. Both tapping attempts are hard to be realized and can easily be revealed. Additionally, in contrast to the heavily regulated RF regime (e.g. by the International Telecommunication Union), there are no bandwidth restrictions for optical communication so far.

Similar to RF communication, modulation of an optical signal can be realized by amplitude, frequency, or phase modulation. The most promising modulation technique for free-space communication is considered to be phase modulation where information is represented by the instantaneous phase of the carrier wave. The phase modulated signal can be demodulated by the use of a coherent receiver where the signal is down-converted to a baseband frequency in the RF regime by the use of a heterodyne or homodyne detection setup.

Coherent optical communication offers the advantage that signals with extremely low intensities can be detected. Theoretically only a few photons are required to detect one bit with a decent error rate. This is achieved by mixing the received signal with a strong optical local oscillator on a fast photo-detector. Furthermore, the received signal can actively be filtered by means of an optical phase locked loop providing a spectral selectivity superior to any available optical filter. Further, it can spatially be filtered by the highly directional received cone. Due to the effective filtering, such a system enables communication even with the sun in the field of view [3].

The laser linewidths required for various modulation formats are listed in table 2.1 for a 10 GB/s link. Binary phase shift keying requires a linewidth of 8 MHz or less, whereas narrower linewidths are required for other modulation formats. However, the performance of the optical links in the table could further be improved if the laser sources would exhibit a narrower linewidth.

Modulation scheme	$\Delta\nu$ for 10 GB/s	Reference
2-DPSK	30 MHz	[4]
4-DPSK	5 MHz	[5]
2-PSK	8 MHz	[6]
4-PSK	250 kHz	[7]
8-QAM	90 kHz	[8]
16-QAM	6.9 kHz	[8]

Table 2.1.: Typical linewidth requirements for various modulation schemes [9] ($\Delta\nu$: linewidth).

Several studies have been carried out and prototypes have been realized towards the development of a laser communication link in space [10, 11, 12], however, budget cuts prevented a demonstration in space in most cases. A summary of the main optical communication links that have been realized in space and foreseen missions equipped with laser communication terminals are listed in table 2.2.

The worlds first optical inter-satellite link has been realized between the European satellite ARTEMIS and the Japanese satellite SPOT-4. Semiconductor lasers and a direct modulation technique (ON-OFF keying) were used within the optical communication terminal called SILEX (Semiconductor Inter satellite Link EXperiment) and data rates up to 50 Mbps (between SPOT-4 and OICETS) were achieved [13, 14].

The first successful demonstration of a coherent optical inter-satellite link has been carried out in 2008 with laser communication terminals by TESAT between the low earth orbit (LEO) satellites TerraSAR-X (Germany) and NFIRE (US) [15, 3]. Until now several hundred communication links have been performed at impressive data rates of 5.6 Gb/s [1, 16]. Furthermore, coherent optical communication from a LEO-satellite to a ground station in Teneriffe has also been demonstrated [17]. TESAT uses a Nd:YAG monolithic nonplanar ring resonator laser (NPRO) source pumped by diode lasers manufactured by the FBH. The phase modulation on the transmitter side is generated by a lithium niobate electro-optical modulator. The LCT has a footprint of 580 x 580 mm. All optical components like pump laser source, NPRO laser, phase modulator, and fiber amplifier are fiber coupled to allow a modular distribution and thus a high degree of flexibility which is advantageous for the realization of demonstrators. A modular approach, however, increases the overall size and weight. Future systems with a commercial background will aim on realizing compact integrated system approaches with less weight and lower volume.

The launch of the satellites Sentinel 1 and 2 (ESA) and Alphasat (DLR) are scheduled for the year 2012 and 2013, respectively. The LCTs on these satellites are supposed to demonstrate the first GEO (geostationary earth orbit)-LEO coherent optical communication link. The LCTs will also make use of Nd:YAG lasers and the aspired data rate is 2.8 Gb/s.

Furthermore, the "National Aeronautics and Space Administration" (NASA) together with the "Jet Propulsion Laboratory" (JPL) plan on increasing the data rate for deep space missions by optical communication links. ESA and the DLR are planning to equip most of their future satellites with LCTs to increase the data rate by an order of magnitude in comparison to current radio frequency links. ESAs target is to realize data rates of 100 Mbps over a distance of one astronomical unit (roughly the average distance between the sun and the earth) with a link availability of more than 95 % [2]. Further research in this field is carried out by the "Japan Aerospace Exploration Agency" (JAXA), the "National Institute of Information and Communications Technology" (NICT), or RUAG Space Ltd. An overview over current research projects and future trends is given in [18].

Modulation	direct, SILEX		coherent, BPSK	
satellite	ARTEMIS (ESA)	SPOT-4 (CNES), OICETS (JAXA)	TerraSAR-X (DLR), NFIRE (USA)	Alphasat (DLR) Sentinel 1+2 (ESA)
LCT mass	157 kg	150 kg, 170 kg	35 kg	50 kg
power consumption	200 W	150 W	120 W	160 W
volume	-	-	0.58 x 0.58 x 0.6 m^3	0.6 x 0.6 x 0.7 m^3
telescope diameter	250 mm,	150 mm 130 mm	125 mm	135 mm
max. optical transmitter power	35 mW	70 mW, 100 mW,	0.7 W	2.2 W
bit error rate	$<10^{-6}$	$<10^{-6}$	10^{-11}	10^{-8}
link distance	<45000 km	<45000 km	<6000 km	<45000 km
data rate	2 Mbps	50 Mbps	5.6 Gbps	2.8 Gbps
laser source	GaAlAs LD	GaAlAs LD	Nd-YAG	Nd-YAG
wavelength	847 nm	819 nm	1064 nm	1064 nm
launch date	12.07.2001	24.03.1998, 23.08.2005	15.06.2007, 24.04.2007	2013, 2012
orbital location	GEO 21.5°E	LEO 825 km, LEO 610 km	LEO 508 km, LEO 350 km	GEO 25°E, LEO 800 km

Table 2.2.: Basic characteristics of existing and foreseen optical communication satellites in space [19, 16].

Typical requirements of a laser source to be used in a coherent optical communication link in space are summarized in the following. The realization of a laser source with a good trade-off between the different performance aspects is the goal of this work.

- sufficiently high output power
  - LEO-(LEO-ground): 1 W
  - GEO-(GEO-LEO-ground): 5 W
- narrow linewidth
  - depends on the modulation technique to be used, see table 2.1
- large mode-hop-free tuning range to lock the receiver local oscillator to the received beam
  - depends on the absolute frequency stability of the laser source, 300 GHz seems to be reasonable for semiconductor lasers
- good beam quality
  - M^2 below 2 in lateral as well as in vertical direction
- small volume, small weight
- high energy efficiency
- space qualified components and space qualified system

Moreover, coherent optical communication is used for earth-bound coherent free-space optical links. However, due to relatively high atmospheric absorption and scattering, laser sources at larger wavelengths than covered by the GaAs-technology are preferred. Since a variety of optical components are easily available, systems have been realized at 1550 nm [20]. However, the lowest disturbance to the data link by the atmosphere can be found for wavelengths beyond 2 µm [21]. To improve the quality of the link, systems are required to compensate for atmospheric turbulences [20].

2.1.2. Further Applications

As mentioned before, the target application underlying this work is coherent optical communication. Nevertheless, narrow linewidth semiconductor lasers are also attractive for a variety of other applications.

Since semiconductor lasers cover a wide wavelength range they are used for applications that require specific wavelengths. A prominent example is spectroscopy for precision measurements where atomic lines are used for absolute frequency stabilization of laser sources. In fundamental physics, narrow linewidth lasers can further be used for time keeping applications, precise measurement of natural constants [22], LIDAR, or distance measurements.

An example where narrow-linewidth high-power laser sources with excellent mechanical stability are employed is presented in [23]. The laser sources at 780 nm are used for Doppler cooling as well as for detection of a Bose-Einstein condensate of ultra-cold Rubidium atoms. The experimental apparatus is housed in a capsule, that is dropped at the ZARM drop tower to allow for 4.5 s of free fall under micro-gravity conditions. An image of the drop tower (left), the capsule (middle) and the Bose-Einstein condensate experimental chamber (right) is depicted in fig. 2.1. The laser sources for these experiments are also developed and realized at the FBH.

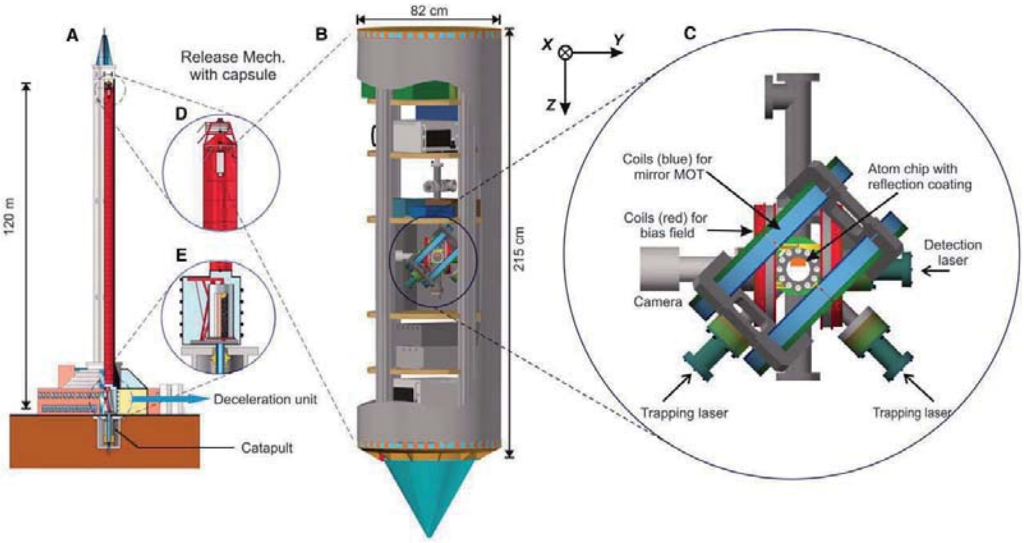

Figure 2.1.: ZARM drop tower (left), capsule (middle), Bose-Einstein condensate experimental chamber (right) [23]. Reprinted with the permission from AAAS.

2.2. Major Technical Developments and State of the Art

Milestones in the development of narrow linewidth semiconductor lasers are summarized in chronological order in table 2.3. The last four results were published by the "Ferdinand-Braun-Institut, Leibniz Institut für Höchstfrequenzetechnik (FBH)"' and the last three can be considered to be the essential results of this work.

The first careful measurements of the spectral linewidth of semiconductor lasers have been carried out by Fleming and Mooradian in 1981 [24]. They measured a 10 MHz linewidth of a Fabry-Perot laser emitting at a wavelength of 832 nm.

Arakawa claimed that the spectral linewidth of semiconductor lasers can be reduced by the use of a quantum well structure [25]. He explained this effect by a reduction of the linewidth enhancement factor which was experimentally confirmed by Noda [26] in 1987 who obtained a linewidth of 10.5 MHz.

In 1992 Bissessur showed that a strained quantum well can further decrease the linewidth [27] and obtained a linewidth as small as 70 kHz at an output power of 10 mW.

$\lambda/4$-shifted DFB lasers feature a stable single-mode operation since the phase shift allows the stop band mode to oscillate. However, longitudinal spatial hole-burning is known to broaden the line of this kind of laser if an abrupt phase shift is implemented. To suppress the effect of longitudinal spatial hole-burning, Okai realized a corrugation pitch modulated (CPM) DFB laser where the effective $\lambda/4$-phase shift is distributed over 360 µm. This device featured the narrowest intrinsic linewidth of semiconductor lasers of 3.6 kHz at an output power of 55 mW that has been presented prior to our work.

Recently, gain guided DBR lasers with a stripe width of 15 µm and a linewidth below 500 kHz have been reported [28]. This is worth mentioning because gain guided lasers are typically not considered to feature a stable single-mode, narrow-linewidth operation.

Until 1993 the linewidth of semiconductor lasers was steadily decreased, whereas later on these narrow linewidths have not been obtained anymore. This somewhat surprising chronological development is explained by the fact that there has been put much effort in obtaining narrow linewidth semiconductor lasers at the end of the eighties and at the beginning of the nineties to realize optical communication over long distances, for instance across oceans by coherent optical communication techniques. After the invention of the erbium doped fiber amplifier [29], direct modulation techniques, that do not require very narrow linewidth lasers, have been preferred.

In recent years, research activities in this field have been steadily growing again. This renaissance is driven by an increasing demand for narrow linewidth lasers in fields like precision measurements and the demonstration of new detection schemes in coherent optical communication [30].

Linewidth measurement results of narrow linewidth MOPA systems have barely been published. One exception is [31] where a bench-top MOPA system using an ECDL as master oscillator with a FWHM linewidth of less than 100 kHz and an output power of 500 mW has been presented.

A lot of the research on narrow linewidth semiconductor lasers has been carried out for DFB lasers due to their potential to emit in a stable single-mode. Further, devices emitting at a wavelength of 1550 nm have been in the focus because this is the standard optical fiber communication wavelength.

Unfortunately, most publications concerning narrow linewidth semiconductor lasers either present a sophisticated measurement and evaluation technique with a modest linewidth (often the linewidth of a commercially available product) or a record linewidth with a non-meaningful measurement setup. Most of all, noise contributions of the semiconductor laser itself (referred to as the intrinsic linewidth in this work) have not been separated from technical noise contributions even though this separation is necessary to understand the spectral performance of the laser. This will be shown in this work.

author	year	$\Delta\nu_{FWHM}$ [kHz]	$\Delta\nu_{int}$ [kHz]	P_{out} [mW]	λ [nm]	laser type	institution
Fleming [24]	1981	10000	-	14	832	Fabry Perot	Lincoln Lab.
Noda [26]	1987	10500	-	5	860	DFB (MQW)	Mitsubishi
Kojima [32]	1988	1050	-	11	866	DFB	Mitsubishi
Kitamura [33]	1990	250	-	4	1530	DFB	NEC Corporation
Matsui [34]	1991	200	-	17	1540	DBR	Oki Electric Industry
Kunii [35]	1991	85	-	10	1500	DBR	Oki Electric Industry
Bissessur [27]	1992	70	-	10	1550	DFB (strain)	Alcatel
Okai [36]	1993	-	3.6	55	1543	CPM-DFB	Hitachi
Smith [37]	1996	39	-	24	1010	DBR	University of Illinois
Lammert [38]	1997	25	-	25	1060	DBR	University of Illinois
Wilson [31]	1998	100	-	500	778	MOPA	University of Otago
Takaki [39]	2002	700	-	100	1550	DFB	Yokohama, Furukawa
Price [40]	2006	20	-	15	850	DBR	University of Illinois
Doussiere [41]	2007	< 300	-	500	1310	DFB	JDS U. Corp.
Vermersch [42]	2008	900	-	70	852	DFB	Thales
Ligeret [43]	2008	800	-	40	852	DFB	Thales
Dias [28]	2011	<400	-	160	990	DBR, gain guided	University of Illinois
Paschke [44]	2010	1091	146	1388	973	DBR	FBH
Spießberger [45]	2010	234	22	116	1066	DFB	FBH
Spießberger [46]	2011	180	2	170	1056	DBR	FBH
Spießberger [47]	2011	100	3.6	1200	1056	MOPA	FBH

Table 2.3.: Chronological development of narrow linewidth semiconductor lasers. The last four publications were published by the FBH and the last three papers (marked yellowish) can be considered to be the groundwork of this work.

It should be noted, that optically pumped solid state lasers, fiber lasers [48, 49], and ECDL lasers [50] can provide narrower free-running linewidths. Furthermore, even narrower linewidths can be obtained by frequency stabilization of semiconductor lasers to high-Q reference cavities where sub-Hz linewidths have been reported [51, 52, 53, 54]. However, all these laser sources require a complex setup and are inferior to semiconductor lasers with respect to one or more of the following aspects: mechanical stability, efficiency, wavelength coverage, size, and weight.