Bassem Arar (Autor)

GaAs-based components for photonic integrated circuits

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Innovationen mit Mikrowellen & Licht

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Motivation

Preamble

The way air traffic has revolutionized our life is indispensable. We check into the boarding machines to travel thousands of miles taking time-saving and safety for granted. In their cockpits, pilots relay on navigation systems, e.g. the global positioning system (GPS), to determine their position and navigate safely into the crowded air corridors. However, the GPS navigation does not provide an error-free transmission of information. The main source of error in GPS navigation systems is the inaccurate time keeping by the clock of the receiver[1]. The key solution for a new generation of navigation systems are quantum sensors. Atom interferometry-based quantum sensors can be used for precise measurement of acceleration and rotation providing the basic platform for ultra-precise navigation systems [1]. They can also be employed for navigation in harsh environments such as in deep-space or under water where the GPS may be extremely disturbed or even unavailable [2]. Further, atom interferometry-based quantum sensors are used for fundamental physics experiments under microgravity (in drop towers or in space) [2], [3]. In order for quantum sensors to be ready to leave the laboratory, appropriate space-qualified and portable laser systems should be available. This explains the increasing interest over the last decade in building compact and robust micro-integrated laser systems for quantum sensors [3].

As an example for applications of quantum sensors, figure 1 shows the laser platform for the QUANTUS-2 laser system[2] for testing the equivalence principle by using ultra-cold rubidium and potassium atoms [4]. In principle, the setup is divided into two parts. The first part uses laser light at the wavelength of 780 nm for the manipulation of rubidium and the other part uses a laser light at 767 nm for the manipulation of potassium. Both parts fill a platform with a total diameter of 65 cm which is integrated in a "capsule". The corresponding quantum sensor experiment is carried out inside the "drop tower" (*Fallturm*) in Bremen[3]. During the experiment, the capsule is dropped inside the evacuated chamber (micro-gravity during free fall on the order of 1×10^{-6} g) of the drop tower. This requires the laser platform to be robust enough to withstand the mechanical stress it is subjected to during the catapult launch and deceleration when caught in polystyrene pellets. For this purpose, the laser system of the QUANTUS-2 experiment uses miniaturized Master-Oscillator-Power-Amplifier (MOPA) laser modules (figure 1). Micro-integrated laser modules are compact devices

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[1] GPS accuracy and error sources: see for example `http://www.mio.com/technology-gps-accuracy.htm`

[2] High resolution interferometry with ultra-cold mixtures in microgravity `https://www.iqo.uni-hannover.de/iqo_quantus2.html?&L=1`

[3] `https://www.zarm.uni-bremen.de/de/fallturm.html`

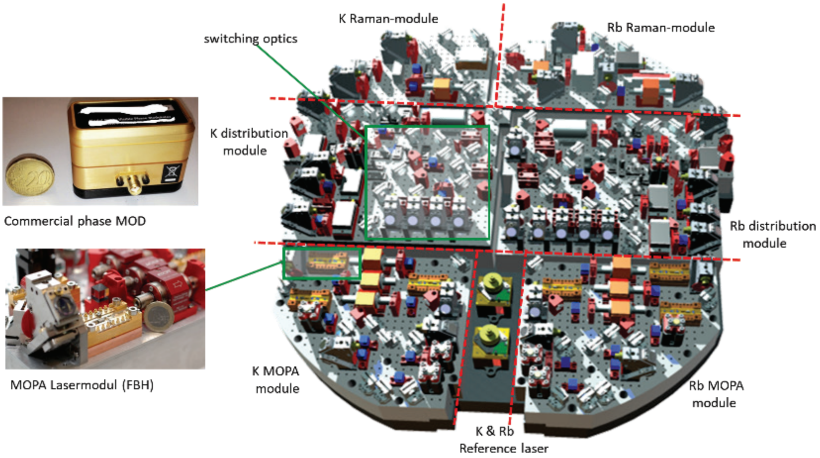

Figure 1: CAD model of the catapult-capable laser system of the QUANTUS-2 experiment for testing the equivalence principle by means of atom interferometry with ultra-cold rubidium (Rb) and potassium (K) atoms.

with a very small footprint. Typically, a micro-integrated laser module consists of a semiconductor laser chip, micro optics, and the corresponding electronic interface. All these elements are micro-integrated on a suitable platform, e.g. aluminum nitride (AlN) ceramic. Hybrid integration techniques (adhesive bonding, soldering) are used to integrate these components on the smallest footprint possible as well as with the highest degree of mechanical stability that can be achieved. The latter calls for omitting any adjustment possibilities after bonding, i.e. any movable parts are omitted. Mechanical stability is achieved through micro-integration simply for geometrical reasons: as the dimension d of an object shrinks down, its mounting surface scales like d^2 while its mass scales like d^3. Further, misalignment through bending scales like d or d^2.

Even with the successful micro-integration of laser modules, the total size of the laser system platform is actually defined by the passive components for signal processing such as beam splitters, fiber couplers, phase and amplitude modulators. In the actual quantum sensor experiments, these devices are only commercially available. The resulting complexity and volume requirement for their integration into laser system platforms are very huge. For example, for the micro-integration of a laser module, typically a footprint of $60 \times 50\,\mathrm{mm}^2$ is required (e.g. the MOPA module in the QUANTUS-2 laser system). The footprint of a (macroscopic) commercial phase modulator for applications at the wavelength of 780 nm is typically about $25 \times 50\,\mathrm{mm}^2$ (see photo on the upper left side of figure 1), where also additional space is required for the deflecting mirrors and lenses for beam collimation. Besides, the macroscopic modulators require high-power drivers (a few *Watt* RF-power) which increases the space requirement of about $350 \times 250 \times 100\ \mathrm{mm}^3$. Further, phase modulators are usually combined with couplers, splitters, and other optical and mechanical components for manipulation of the laser light to generate the necessary signals for the experiments. These "distribution modules" are extremely complex and volume-consuming which is not appropriate for applications in space. Hence, the miniaturization of couplers, phase and amplitude modulators, e.g. by realizing them on the basis of semiconductors (GaAs-based) should reduce the place and power requirements, as well as the complexity of the total optical system which is a prerequisite for field-capable and space-qualified quantum sensors.

For the realization of the GaAs-based components one may benefit from the rich experience that has been made in the field of optical telecommunications (InP-based photonic integrated circuits (PICs) for applications in the range of 1.3 - 1.6 µm wavelength) in which a high level of complexity has been achieved [5]. This requires to adjust the semiconductor technology for the modulators and coupler devices from the telecommunication field into new wavelength ranges, for example, for quantum sensors applications at the wavelengths of 780 nm (for rubidium spectroscopy) and at 1064 nm (hyperfine transitions in molecular iodine at 532 nm [4]).

In this work, GaAs-based phase modulators and couplers should be developed. The aperture of the components should be compatible with the state of the art GaAs-based edge-emitting lasers. This should make it feasible to realize micro-integrated laser and spectroscopy modules that combine passive photonic components (e.g. phase modulators) with active components (e.g. edge emitting lasers). The successful demonstration of these two basic photonic components (GaAs-based phase modulators and couplers) should in the future allow to integrate them on the chip (monolithic integration) which should further decrease the complexity of the system and drastically improve its robustness and reliability.

Micro-integrated laser systems, state of the art

When the passive optical components from this thesis are demonstrated, the next milestone for the future work is to employ these components into the state of the art micro-integrated laser modules.

Micro-integrated laser modules for applications in field and in space have already been demonstrated [3]. For example, an extended cavity diode laser (ECDL) module for potassium spectroscopy is shown in figure 2. The diode laser chip, micro optics, electronic interface, and a micro-thermoelectric cooler (μ-TEC) that carries a volume holographic Bragg grating (VHBG) are all micro-integrated on an AlN ceramic micro-optical bench. The footprint of the device corresponds to $25 \times 80\,\mathrm{mm}^2$ [3].

The deployment of micro-integrated laser modules in fundamental physics experiments in space has been successful. For example, the MOPA platform have been employed in the first optical atomic frequency reference in space, on a sounding rocket [6] (the FOKUS experiment [5]). Shortly thereafter extended cavity diode lasers have been demonstrated in space on-board a sounding rocket and demonstrated reliable frequency stabilization to the potassium D2 line as well as to each other through a

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[4] Optical frequency standard based on molecular iodine for sounding rockets `https://www.physics.hu-berlin.de/en/qom/research/jokarus`

[5] REXUS 9 and 10, see for example: `http://www.dlr.de/desktopdefault.aspx/tabid-6840/86_read-29274/`

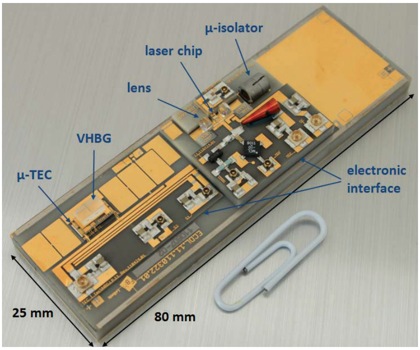

Figure 2: Extended cavity laser module for Potassium spectroscopy. VHBG: volume holographic Bragg grating, μ-TEC: micro-thermoelectric cooler. (taken from [3]).

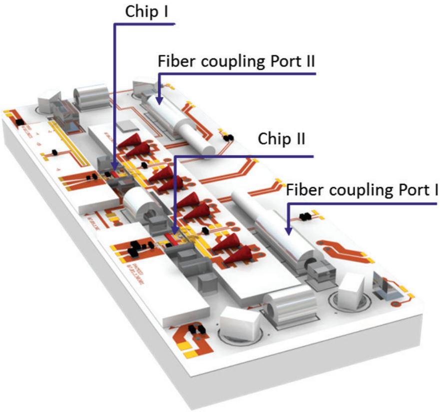

Figure 3: Laser modules based on the Milas technology. The platform allows the integration of two arbitrary SC chips, all together with micro-optics, electronic interfaces, and integrated fiber couplers.

frequency- offset stabilization [7] , and KALEXUS experiment [6]). Both the FOKUS and KALEXUS experiment were sponsored by the German Space Agency (DLR).

However, the platform of the laser module in figure 2 allows for micro-integration of a single chip. To bring the micro-integration technology to the next level, the new platform for micro-integrated optical systems in figure 3 has been developed by FBH within the Milas[7] project. The new platform allows for micro-integration of arbitrary combinations of two semiconductor chips. These combinations may include active components (e.g. diode laser or amplifier chips), as well as passive components (like GaAs chip-based phase modulators). Further, the platform has two fiber coupling ports for input into and output from the laser module using polarization maintaining single mode optical fibers. The Milas technology offers a suitable platform for the micro-integration of the GaAs-based phase modulators that are developed within this work.

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[6] TEXUS 53, see for example: `http://www.dlr.de/dlr/desktopdefault.aspx/tabid-10081/151_read-16493/#/gallery/21758`

[7] Mikrointegrierte Diodenlasersysteme (Milas): supported by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number 50WM1141.

Chapter 1

Introduction

1.1 Developments in III-V semiconductor phase modulators

Milestones in the development of III-V semiconductor-based phase modulators are summarized in chronological order in table 1.1. The last three results are essential results of this work.

Table 1.1: The chronological development of GaAs-based and InP-based electro-optic phase modulators. The last 3 papers are based on this this thesis work.

author	year	waveguide	substrate	junction	λ [µm]	Mod. Eff.** [1/(V · mm)]	losses dB/cm
[8]	1964	GaP	InP	p-n	0.550	75°	-
[9]	1983	InGaAsP/InP	InP	p-n	1.32	-	>10
[10]	1986	GaAs/AlGaAs	GaAs	P-n-N	1.06	56°	-
[11]	1987	GaAs/AlGaAs	GaAs	P-i-N	1.09/1.15	38°/36°	>13
[12]	1987	InGaAs/InP	InP	P-i-N*	1.52	12°	9.8
[13]	1988	GaAs/AlGaAs	GaAs	P-p-n-N	1.06	96°	>12
[14]	1988	GaAs/AlGaAs	GaAs	P-p-i-n-N	1.55	2.9°	1.2
[15]	1989	GaAs/AlGaAs	GaAs	P-I-i-I-N	1.09	28°	20
[16]	1992	InP/GaInAsP	InP	P-I-n-N	1.55	11°	1.0
[17]	1997	GaAs/AlGaAs	GaAs	P-p-i-n-N	1.31	35°	0.6
[18]	2003	InGaAs/InP	InP	P-p-n-N	1.55	34°	<4.5
[19]	2013	GaAs/AlGaAs	GaAs	P-p-i-n-N	0.780	11°	<1.4
[20]	2014	GaAs/AlGaAs	GaAs	P-p-n-N	0.780	23°	<1.4
[21]	2017	GaAs/AlGaAs	GaAs	P-p-n-N	1.064	16°	<2.7

* Multi-Quantum-Wells (MQWs) inside the guiding region.
** Phase modulation efficiency (phase shift in deg/(V · mm))

The first III-V semiconductor electro-optic phase modulators were demonstrated a few decades ago [8]. In 1964, D. F. Nilson and F. K. Reinhart observed for the first time phase modulation of the light signal guided in a reversed biased gallium phosphide p-n junction on InP substrate and related the modulation to the linear electro-optic (LEO) effect. Twenty years later in 1983, H. J. Bach et al. demonstrated phase modulation at the wavelength of 1.32 µm in double heterostructures using InGaAsP p-n heterojunctions for the first time [9]. The authors were also the first to describe the quadratic electro-optic (QEO) effect in p-n diodes. Later in 1986, the first electro-optic GaAs/AlGaAs double heterostructure phase modulator waveguide for integrated optics was demonstrated [10] (operation at the wavelength of 1.06 µm). Since then, GaAs-based phase modulators have received increasing interest for optical interconnects and fiber coupling [22]. The year after, in 1987, J. Faist and F. K. Reinhart reported the orientation dependence of the phase modulation in the GaAs/AlGaAs double heterostructures for laser radiation at the wavelength of 1.09 µm [11]. They measured phase modulation for both, the TE and TM modes for light propagating in the [110] and [$1\bar{1}0$] crystallographic directions in a P-i-N (with an intrinsic (i) core and P (p-doped) and N (n-doped) cladding layers) phase modulator. No difference was found between the measurements for the TM modes in both directions. However, for the TE mode, the LEO effect was found to add in the [$1\bar{1}0$] direction and subtract in the [110] direction. Later in 1988, J. G. Mendoza-Alvarez et al. quantified the contribution of carrier density-related effects to the modification of the refractive index in highly-doped GaAs/AlGaAs double heterostructures. They presented phase modulators at the wavelength of 1.06 µm with a high modulation efficiency (phase shift per volt per unit length) [13] due to contribution from the LEO effect, the QEO effect, and the carrier density-related effect.

As shown by table 1.1 the performance of different phase modulators is characterized by two parameters: the phase modulation efficiency and the propagation losses. For some of these devices, the high modulation efficiency is accompanied with extremely large propagation losses which are caused by electro-optic and free carriers absorption (see for example [13] and [11] in table 1.1). An efficient phase modulator was demonstrated in 1997 by Y. T. Byun et al. [17]. The authors used a so-called W-shape P-P-p-i-n-N-N double heterostructure ridge-waveguide phase modulator and demonstrated a phase modulation efficiency of $34\,^\circ/(\mathrm{V}\cdot\mathrm{mm})$ and very low propagation losses ($0.6\,\mathrm{dB}\cdot\mathrm{cm}^{-1}$). This means that for example for a 2 mm long phase modulator (a typical length of a GaAs-based chip), a phase shift of 180° can be achieved by only applying 1.32 V. The corresponding propagation losses of about 0.24 dB are negligible compared to the coupling losses (typically 2.2 dB for 60% coupling efficiency) which makes this structure very suitable for micro-integration applications. We carefully studied this particular double heterostructure and applied the elements of the W-shaped concept to develop the phase modulators in this work.

1.2 Thesis objectives: GaAs-based passive photonic components

GaAs-based phase modulators require a careful design of the GaAs/AlGaAs double heterostructure in order to efficiently use the electro-optic effects and the free carriers effects in GaAs. For compatibility reasons, GaAs-based couplers in this work are realized based on the GaAs/AlGaAs double heterostructures of the phase modulators. With the successful demonstration of phase modulators and waveguide couplers, as an application of monolithic integration of passive photonic components for future works, an integrated intensity modulator can be realized in the simplest layout of a Mach-Zehnder Intensity (MZI) modulator.

As a medium term target, the passive components that are developed in this work are intended to meet the micro-integration requirements on the hybrid laser modules. These requirements and the specifications of individual components are discussed in details in the following parts of this section.

1.2.1 Objective: GaAs-based phase modulators

The first objective of this work is to realize GaAs/AlGaAs double heterostructure phase modulators.

Principles of phase modulation in GaAs-based waveguides should be investigated. The GaAs/AlGaAs double heterostructures from the literature should be studied to acquire the knowledge to design phase modulators at two different wavelengths (780 nm and 1064 nm). An efficient design requires to model the electro-optic response of the modulator double heterostructure. The design criteria are the phase modulation efficiency (the amount of phase shift per volt per mm), the propagation losses (free carrier-absorption losses, modal losses, and losses arising from the lateral waveguide structure), the polarization maintenance, and the spectral dispersion of the phase modulator.

The waveguide should be achieved based on a ridge waveguide concept. The design should be optimized so that coupling a coherent light signal (laser beam) into and out of the modulator can be achieved using the state of the art micro-optics and micro-integration approaches.

The next step is to realize the phase modulators in the GaAs technology. The realized devices should be characterized. For the characterization, a coherent light signal from a diode laser should be coupled into the modulator and the transmitted power, the polarization, the phase modulation, the residual amplitude modulation, and the modulation bandwidth should be measured. We emphasize here that some of the characteristic parameters of GaAs-based phase modulators such as phase and amplitude non-linear distortion has not previously been investigated in the literature. This is why efforts have to be made within this work to develop new methods for in-depth characterization of GaAs-based phase modulators. These methods should be experimentally implemented.

The required performance of the phase modulator at 780 nm and the phase modulator at 1064 nm is specified as the following:

- single mode waveguides: the ridge parameters (ridge width and etching depth) should be selected for the waveguide to support only the fundamental guided optical mode. This is a requirement for a well-defined phase modulation [19], [23].
- the far field of the modulator's output signal must satisfy the requirements for hybrid integration with active and passive optical elements. Typical divergence angles (95%) are for example 15° in the lateral and 25° in the vertical direction. At these values, the beam can be collimated using commercial lenses to provide a beam diameter that is as close as possible to the optimal value of 0.6 mm [24].
- The 3-dB modulation bandwidth (3 dB/45° phase delay) should be at least 8 MHz (for example for the generation of the sidebands for Rb spectroscopy at 780 nm).

The design of the electrical connection to the modulator should allow for modulation frequencies of at least 8 MHz.

- the half-wave voltage (with direct driving) shall be smaller than 5 V to dispense the demand for diving electronics (a driving voltage of 5 V can be achieved even at bandwidths up to 10 MHz).
- polarization maintaining waveguide: the polarization extinction ratio (PER) is defined as the ratio of optical powers of perpendicular polarizations. The PER should exceed 60 dB provided that the injected beam features a PER of 60 dB or better.
- very low propagation losses: typical values from the literature for low propagation losses in GaAs/AlGaAs double heterostructure phase modulator waveguides are between 0.6 dB cm^{-1} at 1.31 µm [17] and 1.2 dB cm^{-1} at 1.2 µm [14]. The objective is to reduce the propagation losses of the phase modulators in this work beyond the state of the art.

1.2.2 Objective: GaAs-based couplers

The second objective is to realize waveguide couplers. Ridge waveguide couplers should be realized based on the layer structure of the phase modulators. This facilitates the monolithic integration of phase modulators together with couplers for the realization of complex devices such as intensity modulators. A waveguide coupler generally consists of three sections: The input waveguide/waveguides (usually referred to as the *access waveguides*), the coupling section in which the mechanism for transmission of the field into the output channels is determined, and the output waveguide/waveguides. An M to N (or M×N) coupler describes a device with M input waveguides and N output waveguides. In their simplest layout, 2 to 1 (2×1) couplers can be used to combine the optical field from two different input devices into one output path, or as a 1×2 coupler also to split the optical field into two different paths (splitters). Another common coupler concept is the 2×2 3dB coupler with two input waveguides and two output waveguide. The optical field from either of the input waveguides is divided equally (nominally) between the two output waveguides. For the optimum design of ridge waveguide couplers, different coupling concepts from the literature (e.g. evanescent coupling or self-imaging in multi-mode waveguides) should be compared. Wave propagation in 1×2 couplers and 2×2 3dB couplers should be modeled. The design criteria are the excess losses and the accuracy of the splitting ratio of the input field into the output waveguides (imbalance).

Following to the design, the waveguide couplers should be realized and characterized. A coherent light signal from a diode laser should be coupled into the couplers and the transmitted power (the excess loss as a measure), the polarization, and the imbalance between output ports should be measured.

The specifications for the couplers are given as the following:

- operation at the wavelength of 780 nm.
- single mode access waveguides for which the far field of the output signal must satisfy the requirements for hybrid integration with active and passive optical

elements (divergence angles (95%) are 15° in the lateral and 25° in the vertical direction in similar lines to the waveguide of the phase modulators).

- excess loss: for the couplers in this work, the excess losses should be small enough so that when they are used to realize an integrated MZI modulator, the total loss of the modulator is comparable to the state-of-the-art. The excess loss of state-of-the-art GaAs/AlGaAs double heterostructure MZI modulator corresponds to about 8 dB [25]. The MZI is realized using 2 couplers and 2 phase modulators at the actives arms. The length of the phase modulators is typically 2 mm to 4 mm. Assuming that the propagation losses in one phase modulator waveguide are less than 0.5 dB (this follows from the assumption that the propagation losses in the phase modulator waveguide are about $1.2\,\mathrm{dB\,cm^{-1}}$ [14]). If we further assume that the coupling losses are 1 dB or better, the excess loss of the each of the two waveguide couplers should not exceed 3.0 dB.
- imbalance: the imbalance of the input couplers for an MZI modulator translates directly into cross-talk and extinction ratio. For example, the power imbalance of 0.2 dB limits the extinction ratio to 33 dB [26]. Therefore, the imbalance (the splitting ratio) for 1×2 splitter (typically the input coupler of the MZI modulator) should not exceed 0.2 dB in order not to limit the performance of the Mach-Zehnder intensity modulator. A typical value for the imbalance of 2×2 3dB couplers is 0.2 dB to 0.6 dB [26].

1.2.3 Application: GaAs-based amplitude (intensity) modulator

As a proof of concept, the monolithic integration of two phase modulators and two waveguide couplers is demonstrated in the application of a MZI modulator. The optical field fed into the first (input) coupler is divided between the two phase modulators (arms of the MZI modulator) and then the two arms are recombined using the second (output) coupler. The connection between the couplers and the phase modulators (active arms of the MZI modulator) is typically realized using bent waveguides such as S-bends [26]. S-bends are required to guarantee a sufficient lateral spacing between the two active arms so that the modulating electric field can be applied separately on each arm. The design criteria for the MZI modulator are the extinction ratio and the excess losses. In the S-bends, losses may arise due to radiation losses at the bend structure or reflections due to the optical mode mismatch between the straight and the bend waveguides. The S-bends should be modeled and a suitable structure with minimal losses should be found. A suitable concept should be chosen for the input and output couplers of the MZI modulator.

Next, the MZIs should be fabricated and characterized. A coherent light signal from a diode laser should be coupled into the MZI modulator input coupler and the transmitted power (the excess loss as a measure) and the extinction ratio when a modulating electric field is applied should be measured.

We specify the MZI modulator as the following:

- operation at the wavelength 780 nm.
- single mode access waveguides. The far field of the output signal must satisfy the requirements for hybrid integration with active and passive optical elements (as in the phase modulators and couplers).