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Monolithically integrated InP based modelocked ring laser systems

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ABSTRACT

In this paper we report on the progress in the development of modelocked ring lasers that are integrated on a single chip in the InP/InGaAsP material system. With the current optical integration technology it is possible to integrate quantum well optical amplifiers, phase modulators and passive optical components such as waveguides, splitters and spectral filters as standardized building blocks on a single chip. Using such standardized components a number of passively mode-locked ring laser devices have been realized in a standardized fabrication process. Results from a few of these devices are presented here. We have observed a record width of the frequency comb from a modelocked quantum well ring laser operating at a 20 GHz repetition rate. The optical coherent comb is centered around 1542 nm and has a 3 dB bandwidth of 11.5 nm. A minimum pulse width of 900 fs was observed. A second device that is highlighted is a modelocked ring laser with a 2.5 GHz repetition rate. Its 33 mm long cavity is fitted onto a chip of 2.2x1.9 mm². One of the goals of this work is to make such designs available in device libraries for use in more complex integrated optical systems using standardized technology platforms.

Keywords: photonics integrated circuits, semiconductor lasers, ring lasers, mode-locked lasers

1. INTRODUCTION

Over many years now ultrafast laser systems have been researched, developed and used. Such systems are used to investigate many subjects in science and to demonstrate many different applications outside science. Technologically the laser systems have become more compact and rugged through solid state laser technology, in particular through the use of fiber laser technology. Applications such as laser machining, non-linear microscopy and metrology have benefitted from this both in research and in applications. There is and has been much activity to advance the short pulse semiconductor based lasers for many years as well. The interest is driven by the large gain bandwidth that is available. Very nice results have been obtained in research programs but semiconductors have been starting to play a role in commercial short pulse laser systems more slowly. Semiconductors started to have a significant impact inside the laser cavity when they were applied in saturable absorber mirrors in modelocked solid state laser systems enabling robust modelocking at high power1. Modelocked vertical cavity semiconductor lasers that are pumped optically or electrically are now also becoming a successful technology2. However for in-plane semiconductor lasers the progress is more slow. This progress is however most welcome since by using optical integration technology in-plane lasers can now be integrated with other optical devices and complete laser systems can be fabricated on a single chip (e.g.3). For the future, one can envisage even the integration with electronics and microfluidics. Thus useful modelocked lasers that are in-plane semiconductor lasers are of significant interest because of the high level of integration that can be achieved. This will enable a wide range of applications, e.g. in microwave photonics4 and applications in combination with fiber optics such as distributed sensors and telecommunication5 etc..

In this paper we discuss semiconductor integrated passively modelocked ring lasers that have been realized using integration technology in InP/InGaAsP. This technology can be used in the 1.5-1.6 µm wavelength region and it allows for the integration of optical amplifiers, passive waveguide devices, electro-optic modulators, detectors and absorbers on the same chip. This technology is now rapidly becoming more mature and it is now also becoming available from III-V foundry companies through a brokerage organization6. Modelocked ring lasers are of interest not only for reasons of interesting physics due to the two directions in which they can operate, but have clear technical advantages and as we will show are capable of interesting performance.

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We first discuss briefly the integration technology in section 2 and will focus on aspects most relevant to modelocked lasers. A more general overview on laser research and the integration methodology used also in this work is given by Robbins et al. This technology allows for a considerable amount of design freedom for the in-plane modelocked laser. In this paper the focus is on semiconductor ring lasers. These are interesting devices in themselves, but also have specific advantages, particularly with respect to photonic integration. After a brief historic overview we will discuss how this technology can be used to help the design and performance of modelocked ring lasers in section 3. Then in section 4 we present the results obtained from different modelocked ring lasers. The first set of results is from a laser that is producing a record coherent bandwidth. The second laser has the lowest repetition rate reported for an integrated semiconductor modelocked ring laser.

2. FABRICATION TECHNOLOGY

At the COBRA Research Institute much effort has been put into the realization of an indium-phosphide (InP) based photonic integration platform. In such a platform active-passive integration technology is used to realize monolithic photonic chips on which optical amplifiers, passive waveguide devices and electro-optic phase modulators can be combined. Active devices such as optical amplifiers, detectors and saturable absorbers can be realized in pre-defined areas which have an optically active layer stack. Outside these regions the layer stack is suitable for passive waveguiding. In this scheme the light always travels at the same height in the layer stack. The active areas contain four 7 nm wide InGaAs quantum wells separated by 20 nm Q1.25 barriers, embedded in a 500 nm thick Q1.25 waveguiding layer. The wafer containing active and passive areas are fabricated using a selective area overgrowth technique by Metal-Organic Vapor Phase epitaxy (MOVPE) in a three-step process. The active regions can have different lengths maybe used from 30 µm and upward but must have a width of 30 µm since the overgrowth technique is optimized on this width.

Both shallowly and deeply etched elements can be fabricated in the layer stack to form optical ridge waveguides or other devices such as e.g. arrayed waveguide gratings or multimode interferometer (MMI) splitters/combiners. Local planarization with polyimide is used and a Ti-Pt-Au metallization scheme is applied. A schematic overview of the five different types ridge waveguides that can be realized is presented in Figure 1. The ridge waveguides have a width of 2 µm.

![Diagram depicting the five basic ridge waveguide types available in the fabrication technology and used in the devices.](image)

Figure 1. Diagram depicting the five basic ridge waveguide types available in the fabrication technology and used in the devices.

The types include a shallowly etched optical amplifier (SOA) which can provide up to 60 to 70 cm⁻¹ small signal modal gain at the gain peak wavelength around 1550 nm. A shallow etched passive waveguide has a typical propagation losses of typically 3 to 5 dB/cm. Deeply etched waveguides allow for a smaller bending radius (down to approximately 100µm) but somewhat higher propagation loss. By contacting the waveguide and reverse biasing the pn junction, it can be used as a voltage controlled electro-refractive phase modulator (ERM). An electrical isolation section is needed to separate different waveguide sections electrically e.g. in between two SOA sections where one section is reverse biased to form a saturable absorber (SA), or the isolation between different phase modulators. Reflections in shallow waveguides of transitions from the passive to the active areas in shallow waveguides can be kept at -50dB or less. This is of particular importance for interfaces in modelocked lasers and for interfaces of devices integrated with a laser system on the chip since feedback above -50dB can seriously affect the behavior of the laser system. Using software defined building blocks (such as amplifiers and MMIs) in this standardized InP based technology, integrated circuits can be defined and circuit designs can be made relatively quickly. The fabrication can be done together with other devices in so-called multi-project wafer runs. In the fabrication runs in which the devices presented in this paper were fabricated, the layout (i.e. size and position) of the active areas on the chip was predefined. This limited the design possibilities at that time. More recently this limitation was lifted in the COBRA and Smart Photonics technology platforms.
3. MODELOCKED RING LASER DESIGN AND ACTIVE-PASSIVE INTEGRATION

Many mode-locked semiconductor ring lasers reported in literature were developed in material without active-passive integration using ‘all-active’ designs where every component in the ring and the output waveguides contains an active layer stack that must be pumped electrically. Compared to passively mode-locked Fabry-Perot lasers that have two facet mirrors, one SOA section and one SA section, ring lasers are therefore more complicated. In particular their cavity must contain an output coupler structure such as an MMI or directional coupler and that structure has to have current injection. The first monolithic all-active mode-locked semiconductor ring lasers were reported by Hohimer and Vawter in 1993. Their laser operated around 874 nm and produced 1.3 ps pulses. In 1998, Yu et al. reported on realizations in the GaAs/AlGaAs material system of a number of designs of passively mode-locked ring lasers using one or two SAs in the cavity. Issues with the use of an all-active MMI were reported upon. Avrutin et al. in 1999 reported the first passively mode-locked InP/InGaAsP ring lasers. Their design also included two SAs in order to double the pulse narrowing effect of the colliding pulse mode-locking (CPM). In work at our laboratory in 2005 Barbarin et al. reported detailed characterization of a symmetric single SA passive mode-locked InP/InGaAsP ring lasers operating at 15 GHz. These designs used components that were adapted to minimize intra-cavity reflections. In 2009 Heck et al. reported a passively mode-locked ring laser at 1.5 µm with InP based quantum dot gain material. Here it was observed that the laser pulses travelling in the two directions showed different (complementary) optical spectra. McMaster reported on ring lasers in the InP/AlGaNAs system with reduced temperature sensitivity and using a.o. a symmetric dual SA design to increase the stable operating region in 2010.

There are a number of aspects that make that the use of active-passive integration to realize mode-locked ring lasers interesting and highly relevant. The first aspect is the fact that the output coupler and the output waveguides can be realized as passive waveguide structures. In this way the behavior of the coupler becomes more predictable and power consumption can be reduced significantly. The reduction in power consumption was the main motivation for the first laser in active-passive integration reported by Ohno et al. They fabricated a 30 GHz hybridly mode-locked ring laser with deep etched integrated passive waveguides. The same main reason motivated us to start working on this subject. In 2005 we reported on a 27 GHz mode-locked ring laser fabricated using active-passive integration. This device was passively mode-locked but its operation suffered from internal reflections from active-passive transitions and the passive MMI output coupler.

A second well known reason for using ring lasers is that the device does not use facets at the edge of a chip. Thus there is more freedom to place the ring laser anywhere on a chip. This is particularly relevant when the laser is combined with other integrated optical devices. E.g. when one combines a ring laser with e.g. an optical pulse shaper, an optimized short pulse amplifier or optical elements to monitor or stabilize the laser output.

A third aspect concerns the predictability of the repetition rate of the laser. For application of a mode-locked laser in e.g. telecommunication it is important to obtain a specific repetition rate quite accurately. With a ring laser cavity the geometry of the cavity is determined lithographically and uncertainties in cleaving positions are avoided. Recently practical on chip waveguide reflectors have been demonstrated that can be used to make linear laser cavities anywhere on the chip. Thus the length of such devices can be set lithographically as well. In such a device though the SA cannot be very close to the mirror due to the size of the structure of mirror. But a colliding pulse geometry with the SA in the middle of the cavity should be possible. This is however not an optimal geometry for the output power. In a ring laser the device always goes to a colliding pulse mode-locked regime where the counterpropagating pulses meet in the SA. For many applications the repetition rate of the mode-locked laser will have to be stabilized by applying an RF signal to the SA. This brings some flexibility to the range of acceptable free running repetition rates but this is quite limited to 1-2%.

A fourth aspect for wanting to use active passive integration is the fact that the length of the SOA and the SA can be optimized more independently of the repetition rate which is determined by the total cavity length. The low frequency oscillations (low with respect to the roundtrip frequency) of the laser output can be reduced by reducing the length of the SOA. This was demonstrated a.o. by Barbarin et al. for linear mode-locked lasers. With a shorter amplifier, the SOA will have to operate at a higher current and typically this means that the derivative of the modal gain to the carrier concentration (the differential modal gain) is lower. This in turn reduces the amplitude variations driven by the current noise. The length of the SA typically has a fixed ratio to the SOA length mainly. The range of operating parameters of the laser, i.e. the reverse bias voltage on the SA and the forward bias current on the SOA, where the laser shows mode-locking can be optimised in this way as well. This links to the fact that this region of stable mode-locking is not only limited by Q-switching behaviour linked to the SA but is also seriously restricted due to the self-phase modulation of the pulse in the SOA. The self-phase modulation on the pulse is reduced when the SOA is made shorter. This is because the
refractive index change due to the change in carrier density in the SOA when the pulse passes through, will be of a similar magnitude. Thus the phase change is reduced because of the reduced length. One may actually reduce the length of the SOA to the point where the small signal gain of the amplifier at the highest possible current density can just support lasing, i.e. compensate the intra-cavity losses. The amplifier will have to contain sufficient energy to saturate the amplifier which can be arranged by using a wider amplifier. However this is not a standard possibility in our fabrication platform. The limit of the short amplifier brings one to a device that is similar to the semiconductor disk laser where pulses have been demonstrated down to 60 fs. Another advantage of a short amplifier can be that depending on other losses in the cavity, the amplified spontaneous emission (ASE) intensity into the laser modes will be lower when using a shorter SOA. A reduced ASE intensity leads to a reduction the linewidth of the modes and the timing jitter in the high frequency part of the noise and jitter power spectra.

A fifth aspect is that the relative position of the SOA, SA and output coupler in the cavity can be optimised and also that additional optical devices can be included inside the laser cavity. An example of this was demonstrated in our laboratory where it was shown by Tahvili et al that the amount of power in the two directions can be controlled by the relative positioning of the SA and SOA in the ring cavity\textsuperscript{22}. The use of intra-cavity elements e.g. filters, may be used to influence (flatten) the gain spectrum in order to reduce the pulse duration in the laser. This was recently demonstrated experimentally by Parker et al\textsuperscript{23} filters and investigated theoretically by Moskalenko et al\textsuperscript{24} using a travelling wave model\textsuperscript{25}.

4. MODELOCKED RING LASER DEVICES

4.1 20 GHz integrated modelocked ring laser with record coherent bandwidth

From the work of Tahvili et al\textsuperscript{22} and earlier theoretical work we could conclude that the most stable configuration is the one where the pulses travelling in opposite direction in the laser cavity experience the same loss and gain as a function of time. This means that the geometrical lay-out of the laser should be fully symmetrical as well. Given the repetition rate of the laser and the available fixed gain sections this meant that the SOA and SA should be in one and the same active region on the chip. The requirement for symmetry then makes that the SA must be in the middle between two SOAs of equal length. The mask layout of the laser is depicted in Figure 2. It is the same layout as one used by Tahvili et al\textsuperscript{22} but this is a new realisation with a different 4 quantum well gain layer stack. The fabrication was carried out within a multi-project wafer (MPW) run available through the COBRA/JePPIX foundry service\textsuperscript{6}.

![Figure 2. Mask layout of the 20 GHz repetition rate passively modelocked ring laser. The two SOA sections have a common contact (orange). The orange circle is the SA contact. Shallowly etched waveguides are indicated in light blue. Deeply etched waveguides are depicted slightly wider in grey. The insert shows the modifications to one side of the MMI to reduce reflections.](image)

The laser cavity consists of shallow straight and deeply etched adiabatically curved waveguides, the output coupler is a 2 by 2 MMI coupler that has been optimized to minimize reflections. The two SOA sections of equal length of 345 μm and the 30 μm long SA section, have 15 μm long electrical isolation sections (ISO) between them. The ISO sections are angled at 45 degree with the waveguide to avoid reflections. The waveguide is crossing the active-passive transition at 15 degrees angle to minimize reflections at the butt joint. The use of the adiabatic bends avoids the need for waveguide offsets between straight and curved waveguides which also can give rise to reflections. And finally the output waveguides end at the anti-reflection coated cleaved facets of the chip at an angle of 7 degrees.

The chip was mounted on a copper chuck which was temperature-stabilized at 18 °C using a Peltier element. The reverse bias voltage to the SA and the forward biasing to the SOA sections were applied using probe needles. The output light was collected from one of the outputs at a time, using a lensed fiber. We checked there was no influence from any
feedback into the laser from possible reflections of the fibre tip. As depicted in Figure 3 the output light was led via an optical isolator to a high resolution optical spectrum analyzer (20 MHz resolution), a low noise Erbium doped fiber amplifier (EDFA) followed by a polarization controller and autocorrelator, and a 50 GHz bandwidth photodiode with a 50 GHz electrical spectrum analyzer.

![Figure 3. Diagram of the experimental setup for characterizing the passively modelocked ring laser.](image)

The performance of the device was mapped by making automated scans of the SOA injection current and the reverse bias voltage on the SA and recording all data. The range over which the SA reverse bias voltage was scanned is 1.4 V to 4.0 V. The SOA current was scanned from 70 mA to 180mA. It was within these ranges that good modelocked behavior was observed. The threshold of the laser increases with increasing voltage from just below 70mA at 1.5 V at the SA to 90 mA at 4.0 V at the SA. In the modelocked state the output in both directions of the laser is the same as far as we can make out in the experimental setup. E.g. the observed output power for both directions is typically the same value within 0.2 dBm. The output power in the modelocked state goes up to 0 dBm for one direction into a fibre. At the highest voltages (3.5-4.0 V) and currents (170-180 mA) the laser goes into a pure passively Q-switched mode with repetition rates around 1 GHz, where there is almost no signal on the RF analyzer at 10 GHz. When the current value approaches this Q-switching regime the laser is in a modelocked state that has increasing amplitude noise at the lower frequencies. At lower SA voltages (< 3 V) and higher current levels (140 - 180mA) the laser switches to a CW state that is a near unidirectional state with 15dB power difference between the two directions. The laser then also operates in a single longitudinal mode with a side mode suppression ratio (SMSR) that can be up to 30dB. The output power into the main lasing direction approximately doubles when it switches from modelocked to CW operation. In a good modelocked state no low frequency oscillations were observed in the RF spectrum, except for the lowest (acoustic) frequencies.

In this paper we are highlighting two operating points of the laser. The first operating point is one where we have observed a record width of the frequency comb, the second point is where we observed the shortest pulse from the laser. The output high resolution output spectrum of the laser at 154.8mA bias current and 2.0 V reverse bias is presented in Figure 4. The spectrum shows a 3 dB bandwidth of 11.5 nm and a 10 dB bandwidth of 17 nm. This width is to our knowledge a record width for passively modelocked quantum well lasers in the 1.5 µm wavelength region, but it is still less than widths reported from modelocked quantum dot lasers. The spectrum on the RF analyzer shows a clear peak at 19.81 GHz that is 2.4 MHz wide at -10dB and approximately 800 kHz at FWHM. The pulse duration determined with the autocorrelator is 3.8ps assuming the sech² shape of the pulse. However the fit to this pulse shape is not very good. The laser pulse is far above the Fourier limit and quite heavily chirped.

![Figure 4. The widest output spectrum observed from the 20 GHz passively modelocked ring laser. The SOA injection current was 154.8 mA and there was a reverse bias of 2.0 V on the SA. The spectrum was recorded with approximately 100 MHz resolution.](image)
A second operating point we are highlighting here is at an injection current of 90 mA which is close to threshold and at 2.0 V reverse bias on the SA. This operating point is in the range where we observed short pulses according to the autocorrelator (1.9 ps FWHM assuming a sech^2 pulse). We have been able to characterize the pulse in detail using a stepped heterodyne complex spectral analysis method\(^{30,31}\). In this method the output of the modelocked laser is mixed with the light from a tunable single frequency laser on a 50 GHz photodiode. The laser is tuned between each pair of neighboring comb lines and the photodiode signal is recorded in real time using a 50 GHz real time oscilloscope. The time trace contains the frequency and phase information of the beat between all the modes together and those of the beats of the single frequency laser with each of the two neighboring modes. From this information the intensity and phase profile in time of the input pulse can be determined. The advantage of this method is that no amplification that may distort the pulse is required. The downside is that this method takes a lot of time (there are many tens of mode pairs) and requires expensive equipment. This is the main reason that only one operating point was investigated. The result for the intensity and the chirp (the time derivative of the phase) is depicted in Figure 5a.

![Figure 5a](image-url)  
![Figure 5b](image-url)

Figure 5. Measurement results from the passively modelocked ring laser with 90 mA SOA injection current and 2.0 V SA reverse bias. In Figure 5a the intensity and chirp as a function of time as measured using the stepped heterodyne method are presented. In Figure 5b on the right hand side the optical output spectrum is depicted.

In Figure 5b the optical spectrum at this operating point is depicted. The pulse duration we observe is 900fs and a linear chirp over 350 GHz. The signal from the autocorrelator suggest a longer pulse but this difference is attributed to the EDFA used with the auto correlation measurement. The laser pulse is not transform limited as can be seen. If the chirp would be compensated through dispersion by some means to zero, the pulse duration would be 400fs. For a shorter pulse also the intensities of the modes would have to be modified in e.g. a pulse shaper.

An important limitation in the amount of current injected into the SOA of modelocked semiconductor lasers is the current density that is consequently flowing through the SA. In this device we have operated with very high reverse bias current densities of up to 33 kA/cm^2 in the SA. Thus the value of the contact resistance is important for this reason. If it is too high, the SA simply blows up. The contact resistance of the SA plays another role because it can cause the effective voltage over the junction to drop with increasing current. This typically influences the dynamic behavior of the laser\(^3\) since the absorption and absorption recovery times depend on the applied voltage.

As a further development of such ring lasers, we will be investigating the use of intra-cavity elements such as Mach-Zehnder interferometers to flatten the roundtrip gain spectrum in the laser cavity. Another possible further aspect that can be investigated is to separate the two SOA sections further from the SA in a symmetric way as to reduce any overlap of pulses from the two directions in the amplifiers and thus reduce any spatial hole burning effects. Spatial hole burning can modulated the effective modal gain spectrum in the laser. Since a 1 ps pulse is approximately 100 µm long, moving the SOA sections by a few hundred microns should suffice.

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4.2 2.5 GHz integrated modelocked ring laser

The second ring laser device we are presenting in this paper is a 2.5 GHz passively mode locked ring laser. We are presenting here the first results obtained from this device. It is the lowest repetition rate reported for an integrated semiconductor ring laser. The motivation for starting the development of this device is to have a modelocked laser that can be used for Frequency Comb Fourier Transform Spectrometry, in particular with the application of gas detection in mind. In this spectroscopic technique two frequency comb lasers are needed that have slightly different repetition rates and the two frequency combs are stabilized in wavelength with respect to each other.

The repetition rate requirement on the modelocked laser is a compromise between the spectral resolution required and the amount of space required on the chip for a single laser. In Figure 6a the mask layout of the ring laser is presented. Its 33mm long cavity is fitted onto a chip of 2.2x1.9 mm². The cavity is fully symmetrical again for an optimized operating region and it contains a 1.5mm long active region in which the 50 µm long SA and two 700 µm long SOAs are realized. These are located at the top in the middle of the laser. The passive waveguides are all deeply etched to allow for a small bend radius of the waveguides. In this way the cavity could be folded. The output coupler is formed by a 2 by 2 MMI. On the left and right hand side, electro-refractive phase modulators (ERM) that are intended to tune the offset frequency of the comb lines are included.

This mask lay-out was designed using a library of standardized building blocks for the fabrication in the foundry of Smart Photonics B.V.. The chip was realized in a multi-project wafer run. The size of the laser is such that we can integrate two lasers on a single smallest cell on the wafer of approximately 4mm x 4.5mm. A photograph of the realized laser device is presented in Figure 6b.

The laser chip was mounted on an aluminium chuck that was cooled through temperature stabilized water. The contacts on the chip were wire bonded to a printed circuit board (PCB) next to the chip which allows the laser to be connected to the power supplies via a D-sub connector. In Figure 7 we show two initial characterization results that demonstrate the operation of the device as a modelocked laser. In Figure 7a the electrical spectrum from a 50 GHz photodiode signal measured with the RF analyzer is presented. The total injection current is 115 mA and the reverse bias voltage is 2.7 V. It shows a narrow peak at the fundamental repetition rate close to 2.5 GHz (insert) and its harmonics. The fact that the amplitude of the harmonics goes down slowly with frequency already shows that the pulse is short. Also we note that the electrical spectrum shows that the laser is very quiet at the low frequencies. The autocorrelator trace is presented in Figure 7b. This trace belongs to the same operating point as that in Figure 7a. The width of the trace is 14.6 ps which implies an 8 ps FWHM for a sech² pulse shape.
5. CONCLUSION

In this paper we have discussed modelocked semiconductor ring lasers operating around 1.5 µm and realized in InP based photonic active-passive integration technology. The advantages of active-passive integration technology for modelocked ring laser systems were discussed and two recent results were presented that demonstrate a few of the advantages and issues of photonic integration. We have demonstrated a record width for a frequency comb from a modelocked quantum well laser and we have demonstrated the lowest repetition rate for a modelocked ring laser. The integration technology used for these devices is now becoming commercially available and the results we present show that this technology can be used successfully to obtain interesting and record setting devices.

These results on short pulse lasers, earlier results on pulse shaping and amplification as well as work on combining these lasers with other devices such as pulse pickers show that the technology is slowly but surely getting closer to being applicable in applications such as pulse sources for non-linear imaging. Further improvements are required, such as intra-cavity control of the dispersion and manipulation of the gain and optimization of the geometry for short pulse generation. The use of the standardized layer stacks in the semiconductor material and the standardized building blocks in the design allow for the development of a set of (possibly parameterized) devices that can be used by other people in multi project wafer runs. In this way the development of more complex circuits can be accelerated.

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