HIGH-POWER SOURCES OF RF RADIATION DRIVEN BY PERIODIC LASER PULSES*

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Abstract

A short, periodic laser pulses can be applied for phase and frequency locking of RF sources operated in a single-mode regime. In particular, these pulses, irradiating GaAs sample, are able to produce fast modulation of Q-factor (due to inserted time dependent losses) with frequency to be close to natural single-mode oscillation frequency. In a steady state regime a phase of oscillations automatically slaves to provide minimum of the losses in GaAs. Another possible principle is to provide electron beam modulation in a cavity excited by periodically modulated current, the resulted beam with modulated density in this case generates RF power in next output cavity. The necessary exciting current can be provided by means of a DC generator those current due to a photoconductivity is externally modulated with definite frequency by laser which irradiates GaAs isolator inserted in-between electrodes. This klystron principle also solves a problem of phase locking.

INTRODUCTION

Because high-gradient accelerators typically have a photoinjector, where electron bunches are born by laser pulses, it is natural to use RF sources those frequency and phase are controllable by the same laser pulses. A possible scheme, showing how to use these new sources, is shown in Fig. 1.

Many well-known RF oscillators acquire new properties, if one modulates a quality factor of its electrodynamic systems [1]. A switch of Q-factor (Q-switch) might be based on GaAs semiconductor which has several unique properties. Laser radiation with photon energy near 1.43 eV, corresponding to GaAs band gap, causes an induced photoconductivity in a penetration depth ~1 μm so that GaAs becomes an absorber for less than 0.1 ns and recovers itself for ~0.6 ns [2]. At 1 GHz for low electron concentration in the conducting zone (N_e<10^{13} cm^{-3}) GaAs is a dielectric, for high N_e (> 10^{17} cm^{-3}) GaAs is similar to metal, good absorber (to be used for Q-switch) takes place for N_e~10^{15} cm^{-3}. Typical necessary laser power is 1-100 nJ/mm^2 using popular Ti:Sa lasers with wavelength λ=870 nm.

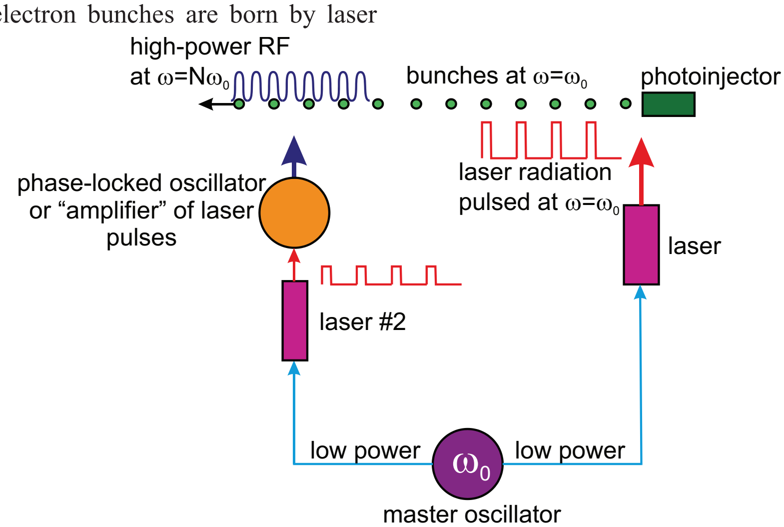

Figure 1: Scheme of accelerator with RF source driven by periodic laser light.

RF OSCILLATORS CONTROLLED BY PERIODIC LASER PULSES

If one irradiates GaAs by pulses cycling with frequency ≤1 GHz and put it in RF cavity, where electrons generate RF power, such a new device might lock frequency and phase (Fig. 2). Indeed, among all possible RF oscillations, which electron beam can excite, only oscillations with a proper frequency and a phase, corresponded to minimum of absorption in GaAs, are able to survive.

This principle was tested in a well known Van Der Pol oscillator, which allows to simulate a non-linear electron device having a threshold of the self-excitation [3]. In Fig. 3 one can see oscillations in dependence on normalized time ($x=\omega_0 t$) in the mentioned generator those

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dimensionless parameter μ, which is responsible for an excess above threshold of a generation (similar to Pierce parameter), was periodically modulated with frequency close to eigen frequency. Note that resulting steady state oscillations in Fig. 3 (black) are placed so that time intervals with negative μ (corresponded to power absorption) lie near zero oscillation magnitude.

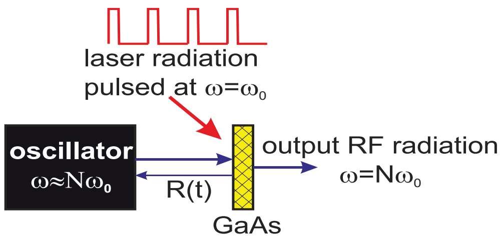

Figure 2: Sketch of RF oscillator locked by periodic laser radiation.

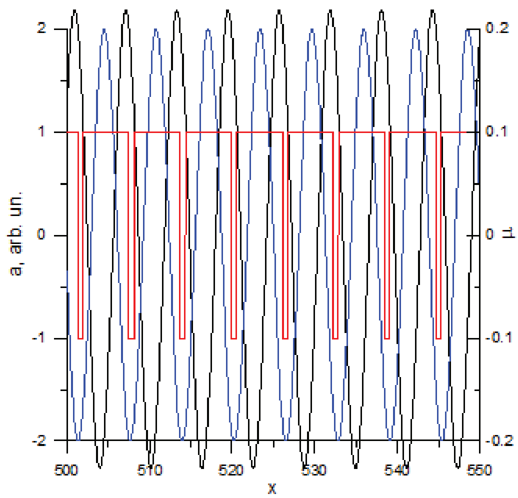

Figure 3: Oscillations in absence of Q- modulation (blue), oscillations in presence of modulation (black), and modulation shape (red).

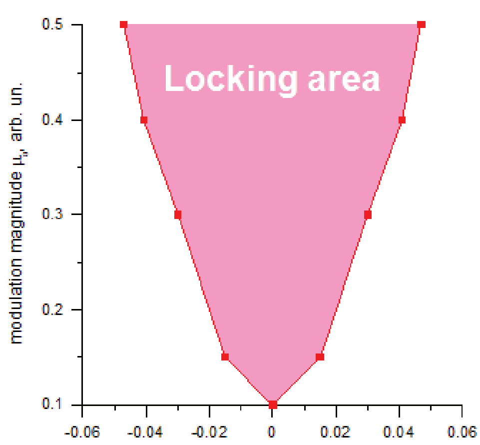

Figure 4: Zone of modulation magnitude which provides locking.

General properties of the described type of phase locking are following:

- Phase locking with accuracy 0/π is possible. 0 or π phase depends on initial conditions and, therefore, might be controlled.
- The far oscillator away a threshold, the deeper modulation is necessary and the longer time to lock (Δt_{min}~1/μ). This is visible in Fig. 4, where locking area is shown in coordinates frequency shift – modulation amplitude.
- The time to obtain phase locking is more for modulation at subharmonics in comparison with modulation at basic frequency (Δt_{min}~N, N – is a number of a subharmonic).

Note that modulation of a conductivity leads to absorption of some RF power in GaAs. These losses do not allow using too powerful and too long pulses. For example, if one takes at f=1 GHz P=100 MW power, τ=1 μs pulse duration, 100 Hz repetition rate and assumes that only 1% of RF power is absorbed in GaAs, average power loss would be 100 W. For GaAs sample of ~1 cm^2 size this value requires intense cooling. Average laser power (10 nJ/micropulse) in this case is not high (~10^{-3} W).

RF AMPLIFIERS DRIVEN BY PERIODIC LASER PULSES

Laser pulses, irradiating GaAs, might also be used for fast periodic commutation of DC voltage or current. The resulted periodic voltage or current are able to excite RF radiation. This allows to modulate beam parameters (density, velocity, etc) in a input low-power cavity of a high-power electron amplifier (Fig. 5).

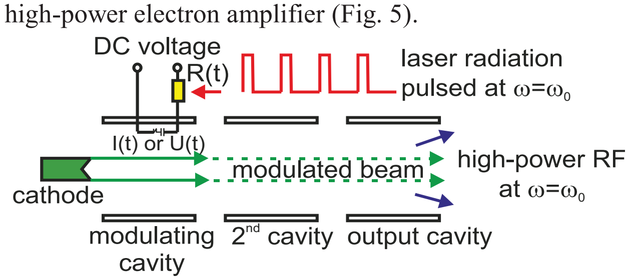

Figure 5: Scheme of klystron those input cavity is controlled and excited by laser pulses switching DC voltage.

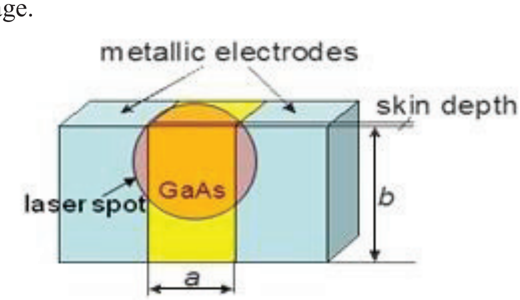

Figure 6: GaAs built-in between two electrodes and irradiated by laser light.

The simplest commutator consists of two electrodes and a piece of GaAs bulk in-between (Fig. 6). If one applies DC voltage to electrodes, the current oscillates in accordance with resistance modulation caused by laser light. A switching laser light should be focused so that it closes electrodes by arisen photoconducting layer.

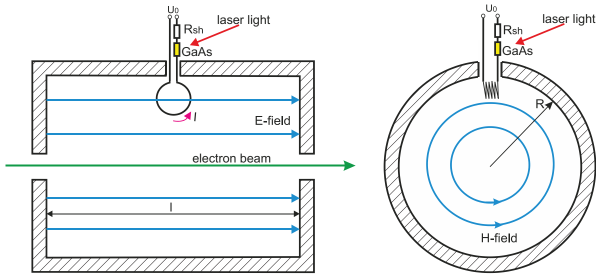

Figure 7: TM_{010} cavity excited by coil with modulated current.

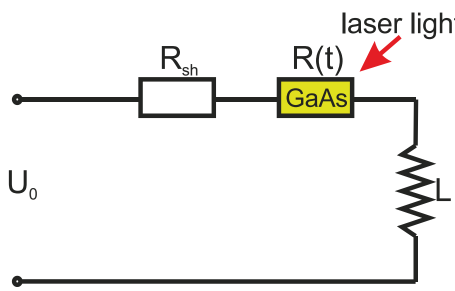

Figure 8: Simple equivalent scheme of current modulator.

Let us consider an example. In Fig. 7 the TM_{010} cavity is shown which is excited by antenna in a form of a coil. The current in antenna is generated by modulation of DC voltage which feeds a time-dependent load (GaAs sample). An equivalent scheme, which can be used in order to calculate current oscillations, is shown in Fig. 8. Let us take DC voltage as high as U=5 kV, modulation frequency f=1 GHz, GaAs size is $a\times b$=2×2 mm^2, radius of coil antenna Rc=25 mm with n=30 wire turns, cavity length is l=100 mm, the Q-factor of cavity is Q=1000 (in a regime without modulation). In accordance with these parameters and laser power W_{las}=10 nJ in each pulse we calculated current for different values of shunt resistance R_{sh} (Fig. 9). As one can see, the less shunt resistance the higher is the achievable peak current. However, the shunt resistance helps to reduce Ohmic losses in GaAs and to avoid a complicated cooling system.

In particular, if shunt resistance is zero, maximum *E*-field at cavity axis reaches almost 20 kV/cm (W_{las}= 10 nJ), but average power loss in this case is about 10 W. On the other hand, if to take the shunt resistance as high as 30 kOhm, the mentioned power loss reduces down to 1 W. This value equals to average power which laser pulses bring into GaAs. Of course, in this case the *E*-field becomes less (~4 kV/cm).

In Fig. 10 one can see how electric field on the axis depends on laser pulse energy. One can conclude that 10 nJ energy is enough to obtain a field which is near a possible maximum. At this laser energy GaAs resistivity is varied from ~100 MOhm (no light irradiation) and to ~1 kOhm (in presence of a laser light).

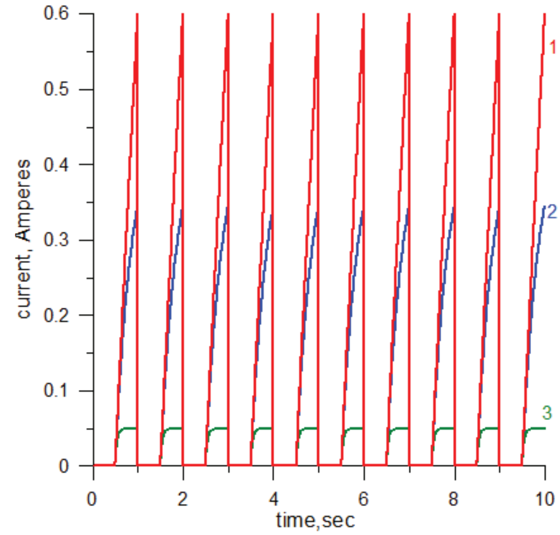

Figure 9: Modulation current in coil antenna: 1 – R_{sh}=0, 2 – R_{sh}=10 kOhm, 3 – R_{sh}=100 kOhm.

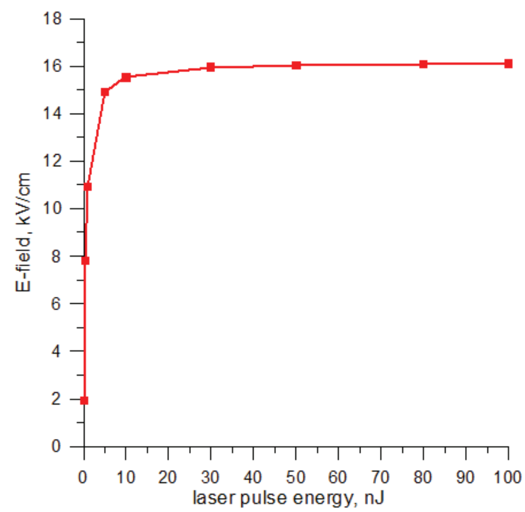

Figure 10: Excited *E*-field in TM_{010} cavity.

Maximum of fields, which can be excited in the cavity, linearly depends on Q-factor value. So, hundreds of kV/cm can be obtained, if to increase Q-factor up to 10^4. Such a quality seems reasonable at low frequencies ($f\leq$1 GHz).

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