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Application of GaAs Power Devices to Very - High - Frequency and High - Efficiency DC to DC Power converters

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Abstract

In this paper a novel possibility to obtain dc-to-dc converters with high efficiency using GaAs MESFET switches is provided. A comparison with standard MOSFET is presented and solutions for reactive element, diode, and driver are proposed. Finally we give an experimental result for hybrid prototype 5V/10V-100MHz converter with an output power of 5W and a power efficiency of 76%.

Introduction

Besides the remarkable advances in high speed technology and system packaging observed over this last decade, the use of high-frequency dc-to-dc converters has been an important step toward the miniaturisation of modern electronic systems that require multi-power level supplies [1]. Notable improvements of power integration technology have also been performed, especially by the introduction of high-frequency ferrite film deposition and multilayered ferrite-core transformers [2] [3] [4] which can support up to 20MHz operating frequency modes. New converter topologies, such as the Zero Voltage Switching and the Zero Current Switching mode converters [5] [6], have been used in order to overcome problems related to the short time commutations at frequencies as high as 5 to 10MHz.

Furthermore, it is shown that the maximum power efficiency expected for scaled converter topologies mainly depends on the parasitic resistances of the switching transistor, its input capacitance, its control voltage and the operating frequency which altogether determine the continuous and the driving power losses in the converter. If we define the switching quality factor of a given type of power transistors by the product of the input capacitance to the on-state resistance ($\nu = R_{on}.C_{iss}$), the GaAs switching transistors compared to MOSFETs would present a switching factor ν at least 8 fold lower and thus lower power losses owing to their intrinsically higher electron mobility and higher energy bandgap [7]. 100-to-200MHz converters would then be feasible but an appropriate power integration technology still has to be perfected [8].

In this paper, an investigation of GaAs capabilities for very high-frequency switching applications is presented and compared to Silicon. GaAs MESFET switches and Schottky rectifiers are particularly studied but other IIIV technologies such as Heterojunction Bipolar Transistor's (HBT's) and Heterojunction Insulated Gate FET's (HIGFET's) can be proposed for power conversion use. A boost converter topology operating in square-wave mode is analysed in order to scale semiconductor devices. Time domain simulation results are reported for equivalent Silicon and GaAs technology devices. We really prove the feasibility of very high-frequency power converters and provide measurements done with hybrid technology prototypes using commercial GaAs power MESFETs and Schottky rectifiers operating at 100MHz. Such very high-frequencies naturally allow us to evoke circuit integration since extremely small size can be obtained.

The Step-Up or the Boost converter

As shown in Fig. 1, the step up converter runs with an energy storage/transfer inductor (L_1), two power switches (T_1 and D_1), and a low-pass filter (C_1). In the continuous switching mode, these components are scaled with accounting for the operating frequency and the output available power.

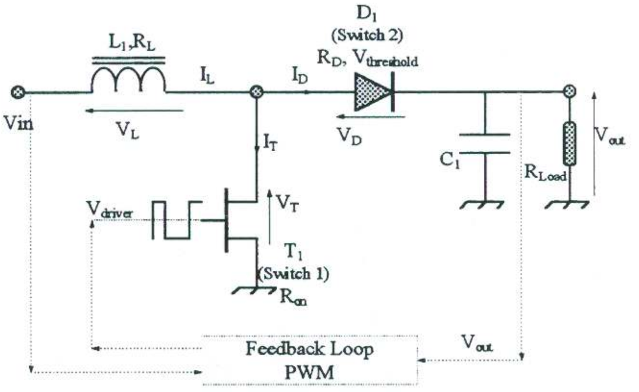

Fig. 1 : The Step-Up converter (the Boost).

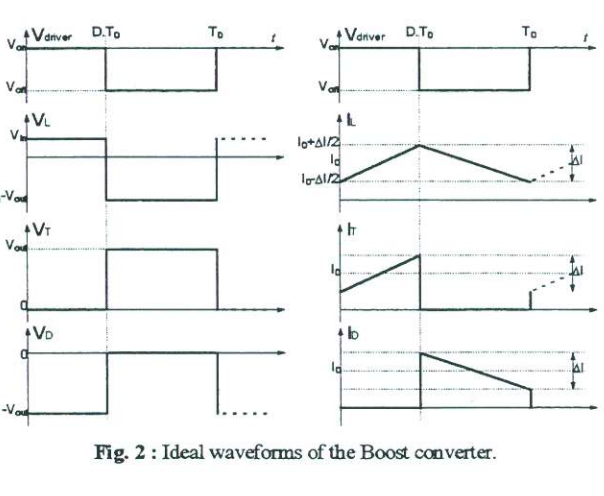

Fig. 2 : Ideal waveforms of the Boost converter.

The signal waveforms presented in Fig. 2 in the steady-state regime give us information about the maximum voltages and currents supported by the different components. For instance, a Boost converter with 5:10V-5W requires a Schottky rectifier and a power MESFET that at least support 12V and 1A. In fact, their switching times would not be as small as in Fig. 2 and thus important switching power losses would occur.

As a first approach, L_1, C_1, the power efficiency η, and the output to input voltage ratio V_{out}/V_{in} can be calculated by considering only the static (or resistive) power losses in L_1, D_1 and T_1, see equations (1), (2), (3)and (4).

$$L_1 = \frac{V_{in} - (R_L + R_{on})I_0}{\Delta I}.D.T_0 \qquad (1)$$

$$C_1 = \frac{D.T_0}{R_{load}.\delta} \qquad (2)$$

$$\eta = \frac{1}{1 + \frac{R_T}{R_{Load}} \frac{1}{(1-D)^2}\left[1 + \frac{\alpha^2}{12}\right] + \frac{V_{threshold}}{V_{out}}} \qquad (3)$$

$$\frac{V_{out}}{V_{in}} = \frac{\frac{D}{1-D} + \left(1 - \frac{V_{threshold}}{V_{in}}\right)}{1 + \frac{R_T}{R_{Load}}} \qquad (4)$$

where

$\alpha = \frac{\Delta I}{I_0}$ and $\delta = \frac{\Delta V_{out}}{V_{out}}$ are the relative ripple of the input current and the output voltage.

$R_T = R_L + D.R_{on} + (1-D).R_D$ represents the effect of the parasitic resistances of L_1, D_1 and T_1.

Equations (3) and (4) give the influence of the parasitic elements R_T and $V_{threshold}$ on the power efficiency and the conversion ratio. Of course, the total parasitic resistance R_T plays an important role in the device optimisation because a compromise should be made between commutation times, breakdown voltages and parasitic resistances while scaling the semiconductor devices.

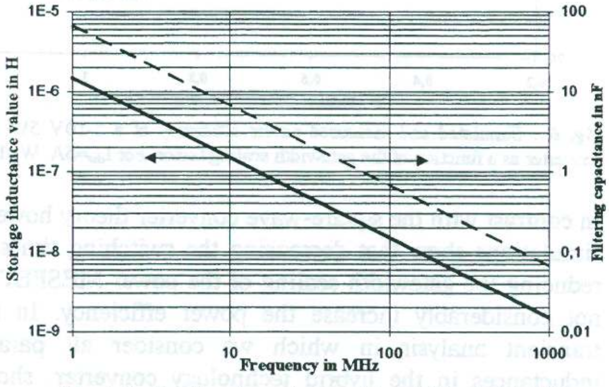

Chart. 1 : Reactive element values L1 and C1 calculated for $\alpha = 2$ and $\delta = 1\%$

On the other hand, we have presented (see Chart. 1) the passive elements L_1 and C_1 as functions of the switching frequency in order to illustrate how the frequency increasing allows to proportionally reduce their size. These values were calculated for a 6:10V, 6W converter.

At 100MHz for instance, only 15nH inductor (which can be made without any magnetic core on a dielectric substrate) and 1nF capacitor are able to maintain the continuous operating mode with 1% output ripple.

High-Frequency converters, comparison of GaAs and Silicon devices

Circuit waveforms previously presented actually do not involve any switching limitations for the diode or the transistor. But in reality, the signal switching times could not be neglected because they can induce very important switching losses in the converter.

Transistors and diodes operating as power switches actually have to be optimised to support high current densities I_{dss} and blocking voltages V_{BD}. Also, they should present small on-state resistances R_{on} and small input capacitances C_{iss} in order to be reduce the static power losses and the switching power losses respectively. For given I_{dss} and V_{BD}, an optimal semiconductor device is obtained when the product $R_{on}.C_{iss}$ is minimal because $R_{on}.C_{iss}$ is proportional to the total power losses in the converter. Its has been shown in [7] that optimised Gallium Arsenide devices, owing to a much higher electron mobility and higher breakdown field strength than Silicon, provide a 12.6 times lower R_{on}, a 9.8 times higher transconductance and a 7.6 higher transition frequency than equivalent geometry Silicon's. By consequence, GaAs devices allow either higher power efficiencies or higher operating frequencies than Silicon.

We present in Fig. 3 power efficiency evolutions of two different technology 6:12V boost converters, GaAs's (top curves) and Silicon's (bottom curves). These results have been performed with the time domain simulator PSPICE using equivalent level of technology Si-MOSFETs and GaAs-MESFETs, with similar dc-characteristic GaAs and Silicon Schottky rectifiers. The power efficiency is carried out as a function of the output available power for various frequencies. They show a rapid efficiency degrading in the case of MOSFET structures but excellent High-frequency behaviour of GaAs MESFET's.

These results do not involve any driver related problems : the driver is supposed to provide commutation times 40 times smaller than the signal period. In practice, for MOSFET based power converters operating at 100MHz, even state of the art CMOS drivers are not able to provide 250ps switching times with important output currents and voltages. GaAs semiconductors however intrinsically permit very rapid switching times owing to their very high device cut-off frequencies. A first driver design is presented in the next section.

allowed us to visualise the signal waveforms showing the same kind of parasitic oscillations. Simulations show that by reducing the parasitic inductances, we could expect strong reduction of these oscillations and then a significant improvement of the power efficiency.

By consequence, at 100MHz and above only a smart power integration technology, which includes the rapid gate drive and the power MESFET and if possible the power diode, can be expected to provide power efficiencies higher than 85%. The component integration technology will allow to use Zero-Voltage or Zero Current Switching techniques which considerably improve the power efficiency.

Conclusion

The hybrid integration of the boost converter allows us to prove the feasibility of 100MHz range converters with good power efficiencies by using GaAs devices. But many improvements could be achieved especially by using a smart power technology for integrating the power MESFET switch and its gate driver in order to reduce driver parasitic inductances.

Moreover, some other IIIV technologies especially HBT's and HIGFET's may be interesting for such applications : actually only positive power levels are required to drive them. In addition for HIGFET's, complementary gate drivers with very good transconductance and output current per millimetre can be achieved.

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