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13nm EUV Free Electron Lasers for Next Generation Photolithography

The Critical Importance of RF Stability

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Introduction

Moore's Law has, since 1965, correctly predicted progress in the field of microelectronics, with technological developments allowing for the doubling of transistor density approximately every two years. Recently, however, transistor density on a silicon wafer is approaching the limits of current technologies, partially due to diffraction phenomena and optical resolution placing a physical limit upon minimum feature size in the field of photolithography. In order to overcome this issue, researchers have been investigating the use of shorter wavelength light in order to push back these physical limits. As a result, the semiconductor industry is currently examining sources of extreme ultraviolet (EUV) light, with wavelengths of 13 nm, to reduce the size limit imposed by using longer wavelengths, and allow next generation photolithography to achieve greater transistor densities than previously possible.

A Free Electron Laser (FEL) is a highly coherent, highly collimated light source capable of creating extremely high power beams of precisely controlled wavelengths. The semiconductor industry is currently examining these as sources of 13 nm extreme ultraviolet (EUV) light for photolithography applications. An important factor to achieve high quality 13 nm FEL emission is the careful development of the amplifying RF system as a complete integrated unit, considering each component as part of the amplification chain to maximise RF stability and FEL beam quality.

Free Electron Lasers as EUV Light Sources

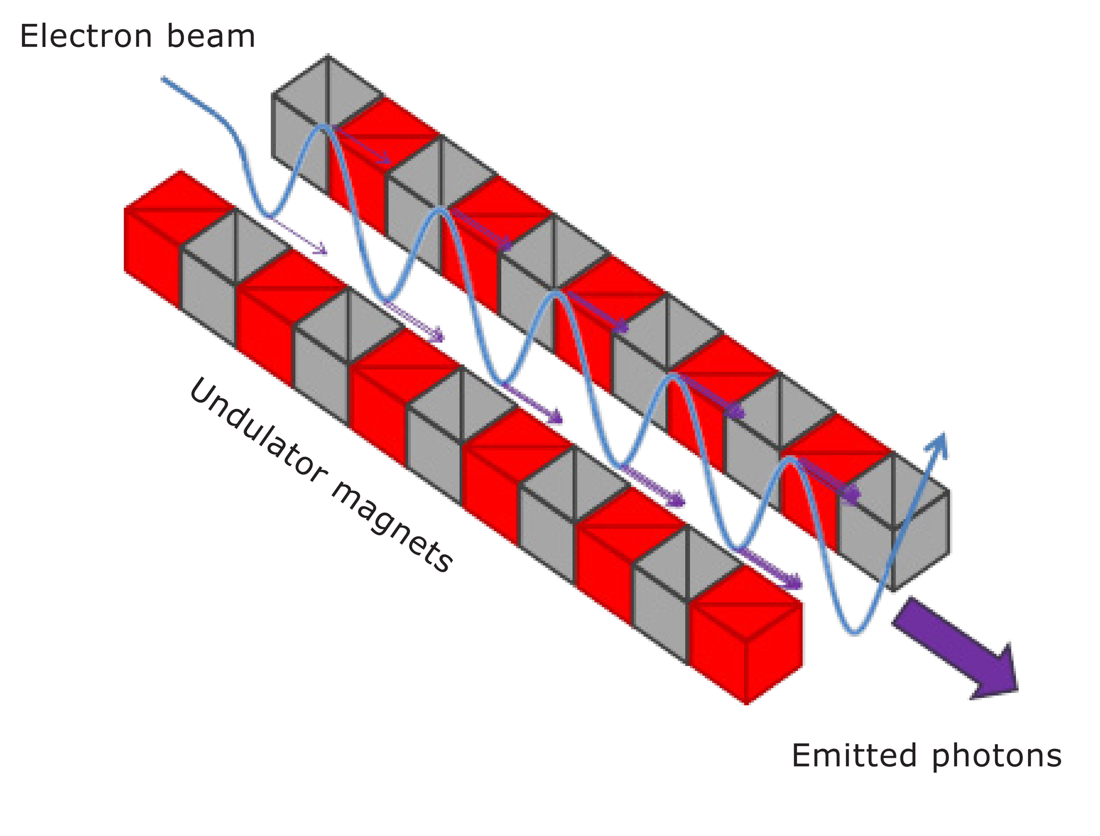

Figure 1: Electron beam passing through a FEL undulator emitting EUV laser light

One source of 13 nm EUV light uses a Free Electron Laser (FEL) system. A FEL is a highly coherent, highly collimated light source capable of creating extremely high power beams of precisely controlled wavelengths. In a FEL system an electron gun produces an electron beam which is directed into a periodic series of opposing magnetic fields, called an 'undulator' or 'wiggler' which causes the electrons to 'wiggle' through the fields, emitting photons each time the course is changed. The frequency of emitted light can be controlled by regulating the energy of the electrons passing into the undulator section.

The Importance of RF Stability

It is well understood that the quality of a 13 nm FEL light source is largely dependent upon the quality of the electron beam [1]. Typically this involves a particle accelerator system. In theory, electrons emitted from the accelerator would have a single energy, and therefore the FEL would receive a constant beam power. But in reality, this power comes from electrons with a finite distribution of energies around a mean value. Any deviation of electron energies results in a distribution of photon energies and, since $E = hf$ (Planck-Einstein relation), also of frequencies and wavelengths. Therefore, an important factor to achieve high quality FEL emission is the careful development of the amplifying RF system, designed with fully integrated, optimized and perfectly matched sub-systems.

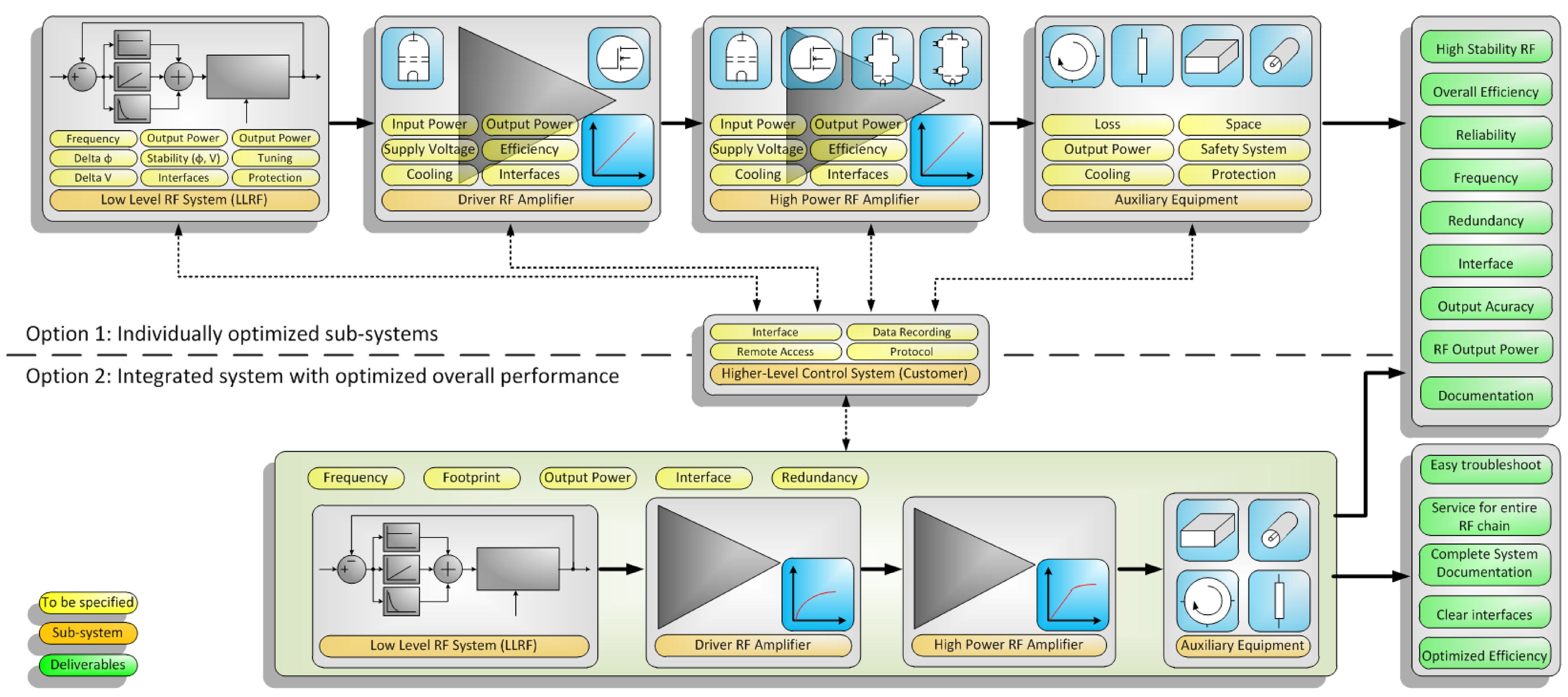

Figure 2: Block diagram showing two RF systems. The first is composed of individually sourced components, while the second is an integrated system.

If the primary requirement of the amplifier is solely to provide high-quality, high-stability RF output, the linearity of output of individual components is unimportant. Therefore, by considering an RF amplifier system as a whole, from LLRF through pre-amplification, to final amplification with all associated sub-systems such as power supplies etc., integrated systems may be designed with additional goals beyond individual linearity and phase stability, such as:

- increased efficiency
- minimised footprint
- flexibility of operation
- start-to-finish documentation
- simplified troubleshooting

Solid-State vs. Tube Technology

While it is widely believed that solid-state amplifiers (SSAs) are the only future of RF amplification technology, replacing tube-based systems such as klystrons, tetrodes and inductive output tubes (IOTs), the technical team at Ampegon conclude that these new developments will come to complement existing technologies, rather than replacing them. As seen in Fig. 3, the different amplifier systems operate in different power/output frequency windows, and offer different technical capabilities.

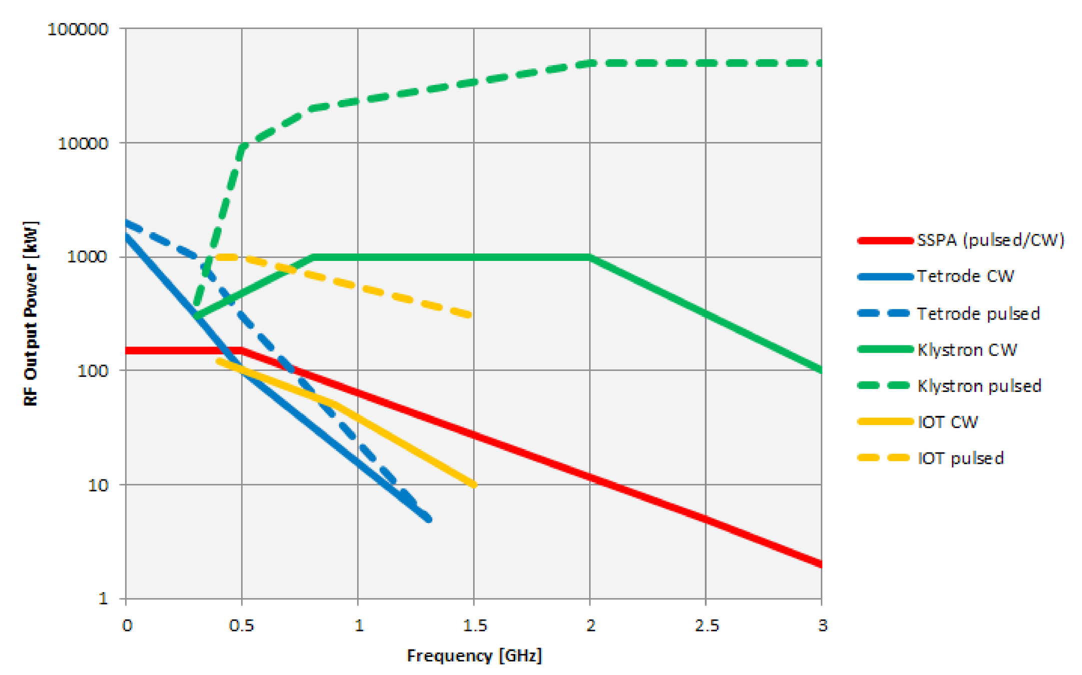

Figure 3: Plot of typical RF power outputs and frequencies for the different amplifier technologies. Note that the solid-state power amplifier (SSPA) operates the same regardless of whether it is providing continuous or pulsed RF output.

Stability and the Optimisation of Efficiency

To investigate how an amplifier system may be optimized, our solid-state amplifier was tested for efficiency across the entire range of possible power outputs and the results compared. The blue trace signifies that the amplifier has been optimised for a specific operating range, increasing the efficiency but reducing the operating window. The red trace signifies the maximum efficiency possible given the opportunity to select both the operating power output window and the drain voltage for maximum efficiency. The phase stability of the output RF was unchanged. By driving the semiconductors beyond the linear response region, greater efficiencies at high output powers were possible. Maximum efficiency is achieved at high power outputs, although the RF output becomes non-linear. However, since the system is fully integrated, linearity is insignificant. The LLRF could be used to generate a signal which resulted in linear RF output when the individual outputs were convoluted. The effect of this ability is to increase the maximum efficiency at high powers by up to 5% or more.

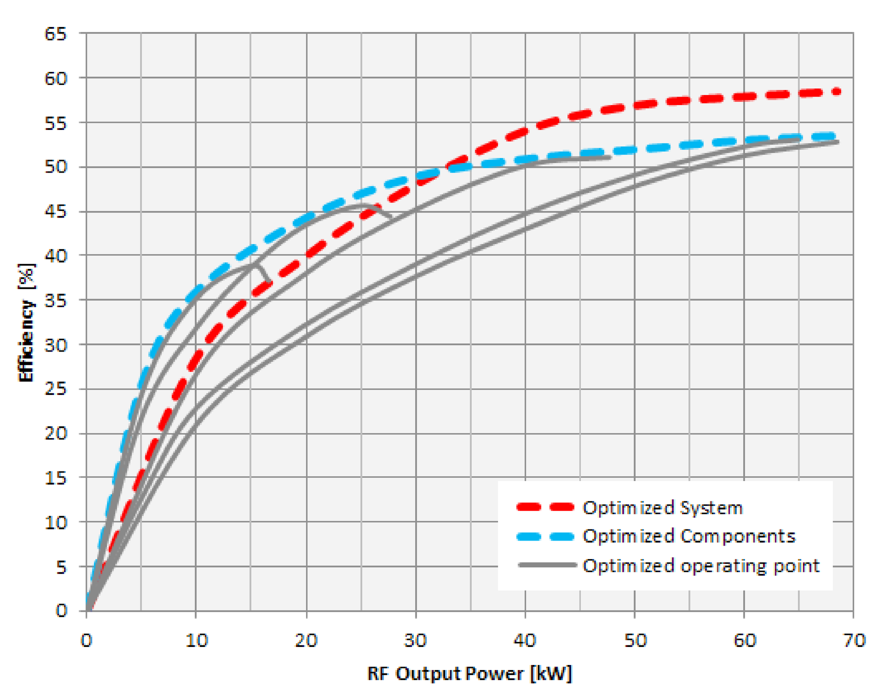

Figure 4: Graph showing possible solid-state amplifier efficiencies given different levels of optimisation.

Conclusions

Cutting edge, next-generation facilities such as FELs proposed for advanced future lithography applications in the semiconductor industry rely upon high quality RF amplifier systems for optimal performance. The industry demands not only extremely high quality RF, but also maximum efficiency, reliability and minimal simple maintenance. Use of integrated RF amplifiers not only improves maximum possible efficiency, but also allows other characteristics to be further optimised for best performance. For FELs, Ampegon offers highly modular and reliable solid-state amplifiers up to 150 kW CW RF amplifiers. For power levels in the range of several 100 kW up to megawatts, highly accurate and stable high voltage power supplies and modulators with maximum accuracy and stability (e.g. pulse to pulse stability of <20 ppm for short pulse applications) have been developed for use with klystrons, IOTs and tetrodes. Fully integrated systems, regardless of whether solid-state or tube-based designs, offer the best solutions for criteria specific to the application.

Acknowledgements

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References

1 B. W. J. McNeil and N. R. Thompson, Nature Photonics 4, 814–821 (2010)