The Goubau Line

bergoz Instrumentation

Surface Waves for Bench Testing of Beam Instrumentation at high Frequencies

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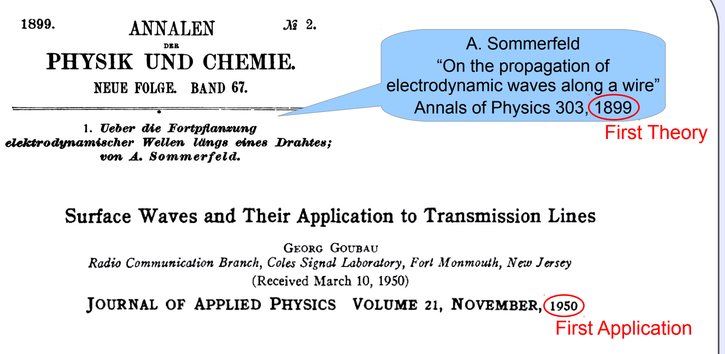
Standard setups for bench testing of beam instrumentation in the workshops usually fail when it comes to signal frequencies a lot higher than 1 GHz. A potential improvement could be provided by electromagnetic surface waves traveling along a single wire. These waves consist of the fundamental TM mode and resemble closely the radial electric and azimuthal magnetic fields around a long and thin beam of charged particles. We discuss their fundamental properties, show how they could be applied and compare calculations to measurements up to 8.5 GHz.



1899. ANNALEN DER PHYSIK UND CHEMIE. NEUE FOLGE. BAND 67. № 2.

1. Ueber die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes; von A. Sommerfeld.

A. Sommerfeld
"On the propagation of electrodynamic waves along a wire"
Annals of Physics 303, 1899
First Theory

Surface Waves and Their Application to Transmission Lines

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First Application

- Maxwell's equations allow a single wire to act like a wave guide that has been turned inside out.
- The wire must have a finite conductivity, a rough surface or a surface coating. In other words, any real wire should be capable of acting like a wave guide.
- The fundamental TM mode can travel along the wire with very low losses. Other modes are strongly damped.
- E_r and H_ϕ around the wire are like the fields around a charged particle beam, but with modified radial dependence.
- There is an additional E_z, but it is weak.

- A fundamental TM mode outside a wire of radius r_w ($r > r_w$) :

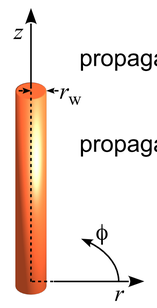
harmonic current I

$$H_\phi = \frac{I\, e^{i(\omega t - hz)}}{2\pi r_w} \frac{H_1^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)}$$

like the fields around a charged particle beam

Hankel functions = Bessel functions of third kind

$$E_r = \frac{I\, e^{i(\omega t - hz)}}{2\pi r_w} \frac{h}{\omega\, \epsilon} \frac{H_1^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)}$$

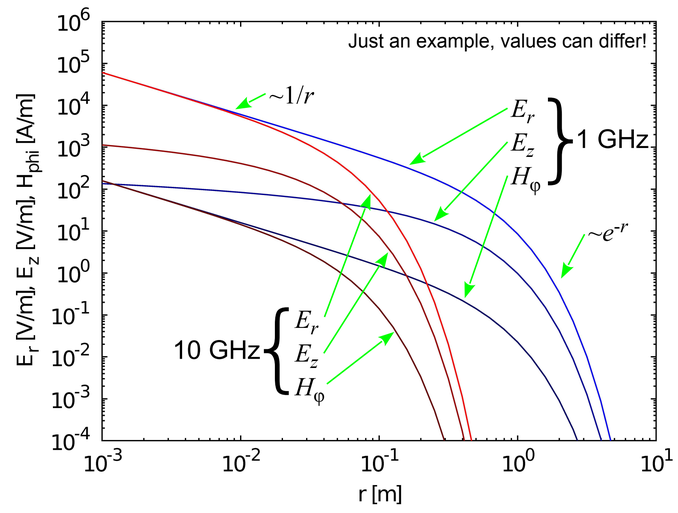


propagation constant of a free wave

$$k^2 - h^2 = \gamma^2 \qquad k = \omega\sqrt{\epsilon\mu} = \frac{2\pi}{\lambda}$$

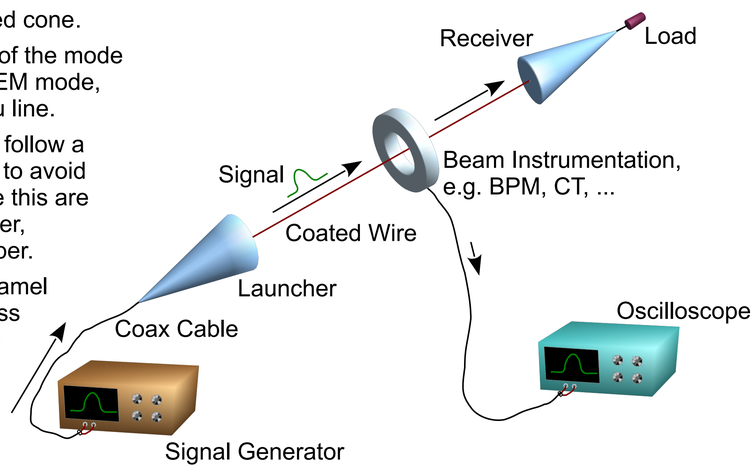
propagation constant of the guided TM mode

$$E_z = \frac{I\, e^{i(\omega t - hz - \pi/2)}}{2\pi r_w} \frac{\gamma}{\omega\, \epsilon} \frac{H_0^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)}$$

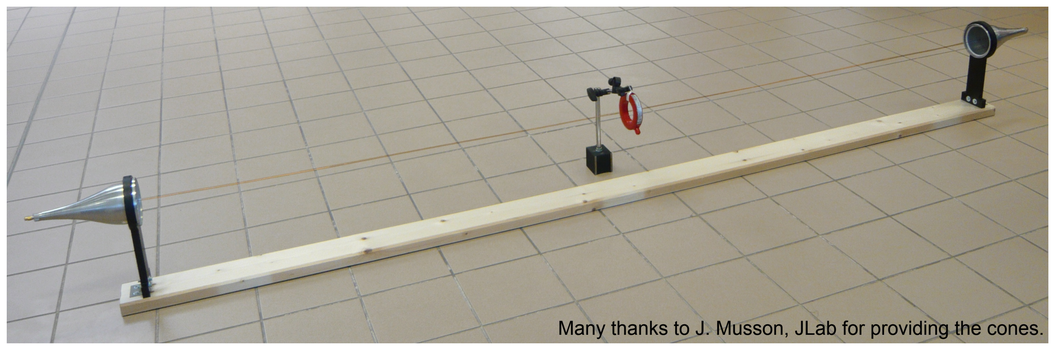


- Near the wire the radial electric and azimuthal magnetic field are proportional to 1/r.
- Further away from the wire the fields decay exponentially.
- Hence, the wave is non-radiating; it is bound to the wire.

- The EM wave on the wire needs to be properly excited.
- For example, by using a tapered cone.
- It has to perform the matching of the mode on a coax cable, i.e. a quasi-TEM mode, to the TM mode on the Goubau line.
- Additionally, the cone needs to follow a well-defined impedance profile to avoid internal reflections. Shapes like this are known as transmission line taper, e.g. Klopfenstein or Hecken taper.
- The wire can be a standard enamel coated copper wire. Its thickness and the thickness of its coating will influence the field extension.

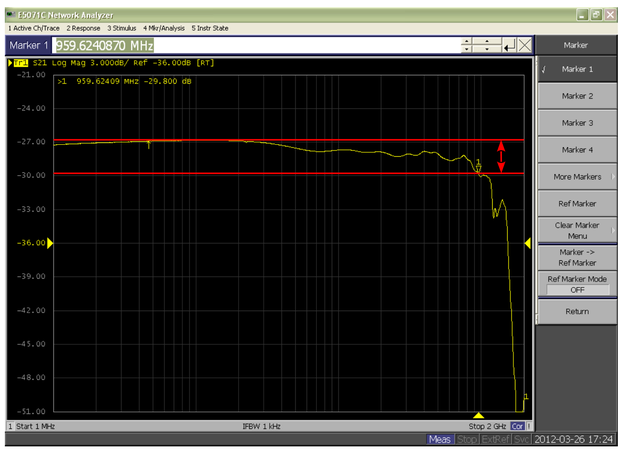


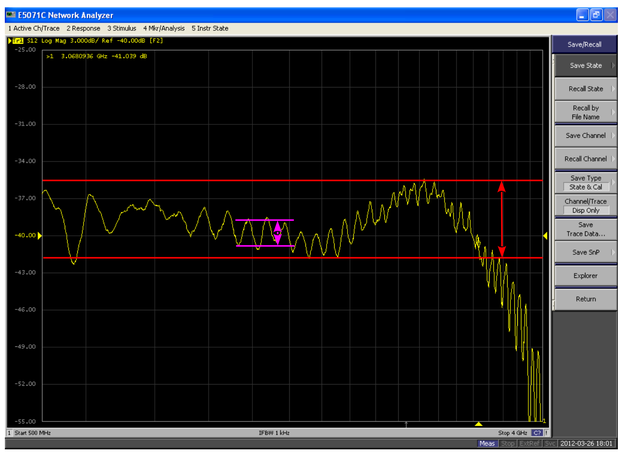
- A Goubau line for bench testing of beam instrumentation.



Many thanks to J. Musson, JLab for providing the cones.

- Our first Goubau line setup is really simple, but it works well. The cones are about 18 cm long and have a diameter of 9 cm. The inner conductors are made from brass tubes of 1 - 7 mm diameter. The wire is a 0.9 mm enamel coated copper wire.
- From measurements we learned a lot and we could confirmed our expectations.
- Though, most importantly we understood what has to be improved.
- Reflections by the cones are limiting performance. Their shape and especially the shape of the conductors inside them need to be improved.

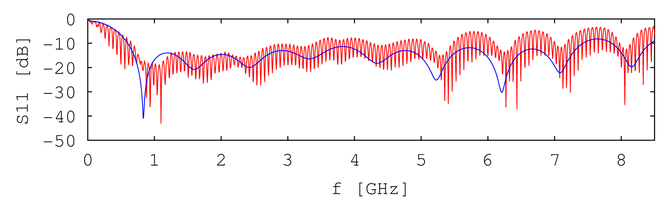




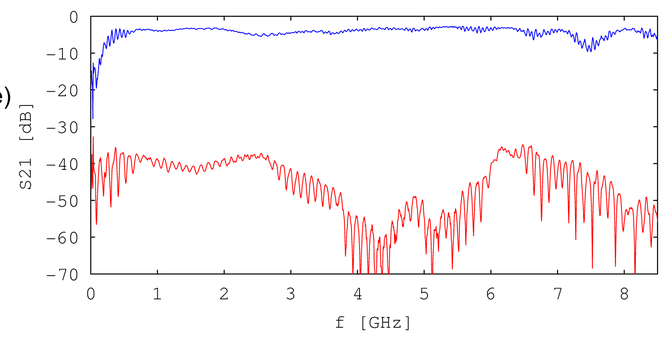
- A current transformer (CT) measured in our standard setup (= "spider").
- The CT was not tuned to achieve a flat response, but has been simplified in the hope to get useful signals at as high frequencies as possible.
- Still, its upper cut-off frequency (-3dB) is at 1 GHz followed by a steep drop.

- The same current transformer measured in our Goubau line.
- Reflections between the cones lead to standing waves which induce a ±1dB ripple in the CT measurement.
- Nevertheless, the CT response lies within ±3dB up to 3 GHz.
- The CT response is lower than in a "spider" because the impedance of the Goubau line is higher than 50 Ohm. Hence, for the same input power the current is lower.

- Measured reflection of our Goubau line (red) compared to calculated reflection of a single cone (blue).
- Standing waves on the Goubau line lead to equidistant resonances.
- Nevertheless, the agreement is good and makes us confident that we understand how we could improve our setup.



- Measured transmission of the Goubau line (blue) and measured response of the CT (red).
- Since the Goubau line transmission is pretty flat one might expect a good CT measurement. But standing waves between the cones spoil the measurement.



- CT response in a "spider" (blue) and CT response in our Goubau line normalized to a 50 Ohm environment (red).
- Around 1 GHz the agreement is good since the "spider" works well and the cone reflection is low.
- Obviously, around 2 GHz there is an artifact in the "spider" measurement, which is absent in the Goubau measurement, i.e. the CT is o.k.
- It is a known problem of the standard setup that it distorts measurements at high frequencies.
- This is the main motivation for studying the Goubau line.